FOURIER ANALYSIS OF GAMMA-RAY BURST LIGHT CURVES: SEARCHING FOR A DIRECT SIGNATURE OF COSMOLOGICAL TIME DILATION

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ABSTRACT

We study the power density spectrum (PDS) of light curves of the observed gamma-ray bursts (GRBs) to search for a direct signature for cosmological time dilation in the PDS statistics with the GRBs whose redshifts \( z \) are known. The anticorrelation of a timescale measure and a brightness measure is indirect evidence of its effect. On the other hand, we directly demonstrate that a time dilation effect can be seen in GRB light curves. We find that timescales tend to be shorter in bursts with small redshift, as expected from cosmological time dilation effects, and we also find that there may be noncosmological effects contributing to this correlation. We discuss the implications of this result on interpretations of the PDS analysis results. We put forward another caution regarding this kind of analysis when we statistically work with GRBs whose \( z \) is unknown.

Subject headings: cosmology: miscellaneous — gamma rays: bursts — methods: statistical

1. INTRODUCTION

Cosmological objects should not only be redshifted in energy but also extended in time because of the expansion of the universe. Time dilation is a fundamental property of an expanding universe. There has been interest in cosmological time dilation as an observational experiment where its effect is large, such as in high-redshift quasar or supernova observations. In order to measure time dilation in light curves of the cosmological objects, it is necessary to find a way of defining the timescale and of characterizing the timescale of variation. The autocorrelation function has also been widely used for this purpose. A number of groups have looked for time dilation in quasar light curves and reported their successes (e.g., Hook et al. 1994), but there seem to be other opinions on the detection (e.g., Hawkins 2001). A more direct observation of time dilation has come from the measurement of the decay time of distant supernova light curves and spectra (Leibundgut et al. 1994; Riess et al. 1997). The results so far published are very convincing and strongly imply that time dilation has been observed. Other cosmological objects where one would expect to see a time dilation effect are the observed gamma-ray bursts (GRBs; Paczyński 1992; Piran 1992).

Observations taken by the BATSE instrument aboard the Compton Gamma Ray Observatory have identified more than a few thousand GRBs and shown that their angular distribution is highly isotropic, implying that GRBs are at a cosmological distance (Paciesas et al. 1999). Observations of the afterglow of GRBs enable us to establish the fact that GRBs are indeed cosmological (Mao & Paczyński 1992; Meegan et al. 1992; Piran 1992; Metzger et al. 1997). If GRBs are at cosmological distances, then the burst profiles should be stretched in time due to cosmological time dilation by an amount proportional to the redshift, \( 1 + z \).

Without knowing the GRB redshifts, different groups (Norris et al. 1994; Mitrofanov et al. 1996; Che et al. 1997a, 1997b; Lee & Petrosian 1997; Deng & Schaefer 1998; Lee, Bloom, & Petrosian 2000) have investigated the correlation of the duration of bursts and the burst brightness in order to look for a signature of time dilation. There have been a number of claims by groups working on GRBs that time dilation is seen in the stretching of peak-to-peak timescales (Norris et al. 1994, 1995; Lee & Petrosian 1997; Deng & Schaefer 1998; Lee et al. 2000).

The expected redshift range of order unity would result in a time dilation factor of a few, while the burst durations cover a large dynamic range from tens of milliseconds to thousands of seconds (Fishman & Meegan 1995). Therefore, a time dilation effect can only be detected statistically. One of the most serious limits of previous works is that inferences are all indirect and possibly misleading since the redshifts of most GRBs are unknown. Norris et al. (1994, 1995) searched for time dilation effects by dividing the bursts into groups based on their peak count rate and comparing some measure of burst duration with peak count rate. They have claimed that brighter bursts had shorter durations than dimmer ones and that the difference between the average durations of bright and dim bursts was consistent with a time dilation factor of about 2. If bursts were standard candles, dimmer bursts would be time-dilated more than brighter bursts, by a dilation factor of \( (1 + z_{\text{dim}})/(1 + z_{\text{bright}}) \), where \( z_{\text{dim}} \) and \( z_{\text{bright}} \) are the redshifts of dim and bright bursts. However, finding cosmological time dilation signature in light curves of GRBs is disputed. For instance, Mitrofanov et al. (1996) finds no time dilation in BATSE using the aligned peak test, and Band (1994) has warned that an intrinsic burst luminosity function could easily produce similar effects. Even if there is a correlation between the duration measure and the brightness measure of the bursts, it is not clear that the argument can be inverted to provide convincing evidence for the existence of time dilation. Questions have been raised as to whether or not the time stretching that is found is due to the intrinsic correlation between pulse width and burst brightness for bursts drawn from a volume-limited sample (Brainerd 1994, 1997). Yi & Mao (1994) also noted that relativistic beaming in either Galactic halo or cosmological models can produce flux-duration relationships that might be consistent with the reported effects. Wijers & Paczynski (1994) suggested a way to distinguish between anticorrelations between flux and duration produced by cosmological time dilation and those produced by a decrease in burst density with distance, which is needed in a local extended halo model if the luminosity function is independent of distance.

It is clear that despite the numerous works published on the subject, time dilation of GRBs remains controversial. Here we present direct results on this topic that differ from those of previous works in two important ways. First, we analyze the...
Fourier power spectra of a sample of GRB light curves to look for such an effect. It provides a significant advantage over other methods, which is relatively easy to interpret. All the timescales of GRB variability are expected to show the effect of time dilation. We do not need to isolate one particular timescale to fit, which may cause artificial results. Second, we use light curves of the GRBs whose redshift \( z \) is known so that we are able to infer the time dilation effect directly. Statistical significance is reduced because of a small size of GRB data sets. Nonetheless, we have a direct measure of time dilation, since we use the GRB light curves for known-\( z \) samples. The number of GRBs whose \( z \) is measured is increasing steadily, and it is worthwhile to attempt directly confirming time dilation effects with the GRBs with redshift information.

2. POWER DENSITY SPECTRUM OF GRB LIGHT CURVES

We have used light curves of GRBs from the updated BATSE 64 ms ASCII database.\(^1\) From this archive, we select the light curves of the GRBs whose redshifts are available. We list the GRBs used in our analysis with BATSE trigger numbers and the reported redshifts in Table 1. We divide our sample into two subgroups so that we separate near and far GRBs. We calculate the Fourier transform of each light curve of GRBs and the corresponding power density spectrum (PDS), which is defined by the square of the Fourier transform of the light curve. Before averaging the calculated PDSs in each subgroup, we normalize GRB light curves by setting their peak fluxes to unity. We compare the slopes obtained by the linear fits as they are without a time dilation correction with those after rescaling to a factor of \( 1 + z \). We have repeated the same process for the light curves of four different energy bands.

In Figure 1, we show the averaged PDSs for the two subgroups of the GRBs divided by the redshifts. Open triangles and squares represent the far and near GRBs, respectively. For the far-GRB subgroup, power in lower frequencies is high, and for the near-GRB subgroup, power is concentrated in high frequencies. This is exactly what one may expect if light curves of GRBs are lengthened due to cosmological time dilation. Instead of removing the individual Poisson noise of a burst from the individual PDSs at high frequencies before averaging, we attempt power-law fits in a limited range, i.e., \(-1.6 < \log f < 0\). The lower bound is determined in that the deviation from the power law begins owing to the finite length of bursts. The upper bound is given such that the Poisson noise becomes dominant. In fact, this is the range where the Poisson noise can be negligible, and consequently the subtraction of the noise can be ignored, as seen in Figure 2 of Beloborodov, Stern, & Svensson (1998). Poisson noise of the time bin becomes important only at high frequencies, \( f \gtrsim 1 \) Hz. Besides, it is the range where the simple power law can be applied (Beloborodov et al. 1998). Dashed lines and solid lines are the best fits of data. Four plots result from four different energy bands of BATSE experiments, as indicated. Flat components at higher frequencies, \( f \gtrsim 1 \) Hz, show Poisson noise.

![Figure 1](http://www.aip.de/~jcg/grbgen.html)

**TABLE 1**

| GRB | Trigger Number | Redshift | Peak Flux |
|-----|----------------|----------|-----------|
| GRB 000418 | 8079 | 1.118 | 1.6542 |
| GRB 991216 | 7906 | 1.02 | 91.481 |
| GRB 990510 | 7560 | 1.619 | 11.283 |
| GRB 990506 | 7549 | 1.3 | 25.122 |
| GRB 990123 | 7343 | 1.60 | 16.962 |
| GRB 980703 | 6891 | 0.966 | 2.9310 |
| GRB 980425 | 6707 | 0.0085 | 1.2451 |
| GRB 980703 | 6665 | 3.9 | 13.848 |
| GRB 971214 | 6533 | 3.42 | 2.6490 |
| GRB 970508 | 6225 | 0.835 | 1.2816 |

Note.—The redshifts are quoted from a compiled table at http://www.aip.de/~jcg/grbgen.html.

**TABLE 2**

| CHANNEL | Uncorrected Slope | Corrected Slope |
|---------|-------------------|-----------------|
|         | Far | Near | Far | Near |
| 1        | -1.7064 ± 0.115 | -1.5436 ± 0.109 | -1.5646 ± 0.149 | -1.5082 ± 0.097 |
| 2        | -1.8052 ± 0.101 | -1.5220 ± 0.109 | -1.5857 ± 0.144 | -1.4652 ± 0.095 |
| 3        | -1.8811 ± 0.103 | -1.5105 ± 0.095 | -1.6008 ± 0.159 | -1.4160 ± 0.090 |
| 4        | -1.3714 ± 0.127 | -1.0989 ± 0.070 | -1.3985 ± 0.150 | -1.1130 ± 0.059 |

Note.—Fittings are repeated before and after correction of a time dilation effect by a factor of \( 1 + z \).

\(^{1}\) See ftp://cossc.gsfc.nasa.gov/pub/data/batse.
obtained slopes are subject to the range used in the fitting process. However, the trend is hardly affected; that is, the subgroup of far GRBs results in steeper slopes than that of near GRBs. For all channels, the subgroup of the GRBs with higher redshifts results in exclusively steeper slopes compared with that with lower redshifts. The slopes of channel 4 show that peaks in higher energy bands are narrow in general.

To see the effects of time dilation, we rescale the time interval of the individual GRB light curve by a factor of \((1 + z)^{-1}\), where \(z\) is the redshift of the individual GRB. This should remove the effect of time dilation, that is, the difference of slopes in the two subgroups resulting from cosmological time dilation. This manipulation has the effect of shifting the contributions of all GRBs to the range of higher frequencies. Resulting slopes of the fits are shown in Figure 2 and summarized in Table 2. We note that the removal of the \((1 + z)^{-1}\) factor makes discrepancies of slopes in two subsamples reduced indeed, but marginal differences still remain.

3. DISCUSSION

Claiming time dilation in light curves of GRBs with the anticorrelation of a timescale measure and a brightness measure has several difficulties. One difficulty is that this effect is correct only for standard candle sources with a standard duration, which we have evidence is not necessarily true (Kim, Chang, & Yi 2001; Chang & Yi 2001). A broad luminosity function and/or an intrinsic spread in the durations could smear out the signature. Another possible difficulty with this anticorrelation is that it could be mimicked by intrinsic properties of the sources (Brainerd 1994, 1997; Yi & Mao 1994; Wijers & Paczyński 1994). An additional complication is that an intrinsic redshift of the time profiles from higher energy bands to lower energy bands may be present (Fenimore & Bloom 1995), which would bleach the cosmological signature.

We investigate the correlation between redshifts and timescale measures using available GRB data with known \(z\). Unlike past indirect searches for cosmological time dilation, we use the GRBs whose \(z\) is known at the expense of statistical significance. Diverse timescales shown in GRB light curves may result from cosmological time dilation of bursts or from intrinsic properties of burst sources. The correlations among pulses within individual bursts give a measure of the intrinsic effects, while the correlations among bursts could result from both intrinsic and cosmological effects. We find that timescales tend to be shorter in bursts with small redshift, as expected from cosmological time dilation effects, but we also find that there may be noncosmological effects contributing to this correlation. The implication of our analysis is that light curves of the observed GRBs show both intrinsic and cosmological effects. It is shown in Figures 1 and 2 that removing the time dilation effect indeed reduces discrepancies in trend of timescale in the two subgroups divided by the redshifts. However, it is not clear that differences remained after taking into account that a dilation effect is due to other effects pointed out previously (e.g., Brainerd 1994, 1997; Yi & Mao 1994). Because of the small number of data, it is inconclusive that these imperfect corrections require explanations other than cosmological time dilation. The amount of observed stretching may not be the value expected from cosmological time dilation alone (Horack, Mallozzi, & Koshyt 1996; Mészáros & Mészáros 1996). Challenging questions then are whether one may extract information on intrinsic properties of individual GRBs or whether one may distinguish a cosmological model by an analysis of the slope of the observed PDSs of GRBs.

Another important implication of our study should be pointed out. Beloborodov et al. (1998) applied the Fourier transform technique to the analysis of light curves of long GRBs. They claimed that, even though individual PDSs were very diverse, the averaged PDS was in accord with a power law of index \(-5/3\) over 2 orders of magnitude of a frequency range and that fluctuations in the power were distributed according to the exponential distribution. With due care, such analysis may yield valuable information of the central engine of GRBs (Panaitescu, Spada, & Mészáros 1999; Chang & Yi 2000). However, the averaged power-law index and the distribution of individual power should be corrected first in terms of a time dilation effect before making any physical determinations from the results of the PDS analysis. We have followed similar procedures for the total sample as Beloborodov et al. (1998) did and obtained the slopes \(-1.6074 \pm 0.105, -1.6423 \pm 0.099, -1.6876 \pm 0.094,\) and \(-1.2190 \pm 0.086\) from channels 1–4, respectively, which are indeed close to the reported value of \(-5/3\). However, these slopes become flatter when the time dilation correction is made before the analysis, that is, \(-1.5253 \pm 0.112, -1.5184 \pm 0.114, -1.506 \pm 0.122,\) and \(-1.222 \pm 0.087\) from channels 1–4, respectively. This flattening can be also seen in Table 2 and is obviously expected if time dilation exists in light curves of the observed GRBs. Therefore, interpreting the power-law index and its power distribution may not be straightforward unless we understand how the light curve is stretched or even contracted.

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