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Statistical Properties of the Highest Pulses in Gamma-Ray Bursts *

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Abstract We study the statistical properties of the highest pulses within individual gamma-ray bursts (GRBs). A wavelet package analysis technique and a developed pulse-finding algorithm have been applied to identify the highest pulses from burst profiles observed by BATSE on board CGRO from 1991 April 21 to 1999 January 26. The statistical light curves of the highest pulses in four energy channels have been derived by an aligning method, which illustrate the temporal evolution of the pulse emission. Our result that narrower pulses go with higher energies is consistent with previous findings. By normalizing both the pulse durations and counts to unity, "characteristic" profiles of the highest pulses in the four channels are also derived. The four characteristic profiles are turned out to be almost the same, thus strongly support the previous conclusion that the temporal profiles in different energy channels are self-similar and the previous conjecture on GRB pulses, implying that the emission process is similar at different energies. The cosmological time dilation effect is examined by investigating the relationship between the pulse flux and pulse duration. An anti-correlation between the two was found, which agrees with the expectation of the cosmological time dilation effect. Also, the evolution of the pulse duration with the observational epoch is studied. The result shows that the pulse duration tends to be shorter in later epochs. This trend cannot be explained by the present theoretical models, and may represent a great challenge to current theories.

Key words: gamma rays: bursts — methods: data analysis

1 INTRODUCTION

The phenomenon of gamma-ray bursts (GRBs), which was discovered three decades ago (Klebesadel et al. 1973), is still a mystery. Before the launch of CGRO, it seemed to be a rare

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phenomenon. The BATSE on board CGRO revolutionized the GRB observations. During its 9-year observations, more than 2700 bursts have been detected — about one burst detected per day. More than 3000 bursts have been detected by all the space-based instruments so far. These bursts have very complex temporal structures. Their temporal profiles are enormously varied —no two of the bursts have ever been found to have exactly the same temporal and spectral development. The temporal activity is suggestive of a stochastic process (Nemiroff et al. 1993): its diversity seems to be random realizations of the same process that is self-similar over the whole range of timescales. Some attempts to quantify the structures have not been successful (e.g., Fishman 1999).

According to the fireball shock model, GRBs are produced as a result of internal shocks when a fast moving shell runs into a slower moving one that was ejected at an earlier time (e.g., Rees & Mészáros 1992). The central engine that powers the fireball into space and generates the shocks is the most difficult part of the GRB-modelling. The most popular cosmological central engine models are merger of two compact objects, and failed supernova (or collapsar, hypernova). Other possible models include rapidly spinning, strongly magnetized compact objects, phase transition of compact objects, and accretion onto massive black holes (see a review by Cheng & Lu 2001 and the references therein).

A great debate on the origin of GRBs had been going on for almost three decades since the phenomenon was discovered. Before 1997, no afterglows from this transient phenomenon could be observed and the question that GRBs originated from the Milky Way Galaxy or from galaxies at large was still controversial. Then, in 1997, a landmark in GRB observation was made by the BeppoSAX satellite when it detected a GRB afterglow on Feb. 28, 1997 (Costa et al. 1997). Since then, more and more GRB afterglows have been observed: the study of GRBs had come to the afterglow era. Significant development on the theoretical models of GRBs has been made based on new signatures from the observations of the afterglows. Huang et al. (1998a,b), Wei & Lu (1998), and Dai et al. (1999) proved that the fireball will usually become non-relativistic and adiabatic just a few days after the burst. Huang et al. (1999a,b) generalized the equation of dynamical evolution of the fireball model so as to be applicable to both ultra-relativistic and non-relativistic regimes, and for both radiative and adiabatic fireballs. The observations on GRB afterglows reveal new information on GRBs, which were not be predicted by the standard fireball model. Some possible effects, such as the effect of non-uniformity in the fireball environment (Dai & Lu 1998c; Chevalier & Li 1999, 2000; Wang, Dai & Lu 2000), that of additional energy injection from their central engine (Dai & Lu 1998a, b, 2000; Rees & Mészáros 1998; Panaitescu et al. 1998), and beaming effect (Dai & Gou 2001; Huang et al. 2000a, b, c), have been taken into account to improve the standard fireball model.

Although significant progress on understanding the nature of GRBs has been made in recent years, the phenomenon still remains a mystery. Statistical analysis is helpful for understanding the nature of the phenomenon and provides constraints on the theoretical models. For example, the bimodal distribution of burst durations (Kouveliotou et al. 1993; Qin et al. 2000), the significant differences of pulse timescale in short and long bursts (Liang et al. 2002), and the fluence-hardness correlations in the two classes of GRBs (Liang & Xie 2002) may indicate the existence of two intrinsically different kinds of progenitors; the statistics of burst duration and pulse duration of GRBs may provide information on the time dilation effect (e.g., Norris et al. 1995), and some restriction in the peak energy - burst duration distribution may give a new clue to the relation between the emission region and the central engine (Liang et al. 2002). In this work we focus on the statistical properties of the pulses in the GRB light curves. To ensure a result of high quality, we restrict our investigation to the highest pulses in the bursts, for which we have the highest signal-to-noise ratios.

It is well known that most of the observed profiles of GRBs are composed of pulses, each pulse comprising a fast rise and an exponential decay (Desai 1981; Fishman et al. 1994). Some methods have been developed for analysing the pulses, for example, the parametric analysis in model fitting (Nemiroff et al. 1993; Norris et al. 1996), the auto-correlation method (Fenimore et al. 1995), the nonparametric method (Li & Fenimore 1996), the peak alignment and normalized flux averaging method (Mitrofanov et al. 1996, 1998; Ramirez–Ruiz & Fenimore 1999, 2000), and the pulse decomposition analysis method (Lee et al. 2000), etc. These statistical studies have revealed part of the observed temporal signatures of pulses from different aspects. The pulses are hypothesized to have the same shape at all energies, differing only by scale factors in time and amplitude ("pulse scale conjecture"). In addition, the pulses at the different energies are hypothesized to start at the same time, independent of energy ("pulse start conjecture"). The two conjectures were confirmed by Nemiroff (2000) in individual bursts. In general, the higher energy channels show shorter temporal scale factors (Norris et al. 1996; Nemiroff 2000). It is found that the temporal scale factors of a given pulse measured at different energies are related to that energy by a power law, and that this possibly indicates that a simple relativistic mechanism is at work (Fenimore et al. 1995; Norris et al. 1996; Nemiroff 2000). A succinct pulse model, which well describes many pulse shapes, was proposed by Norris et al. (1996):

$$I(t) = \begin{cases} I_0 e^{-(\frac{|t-t_{\max}|}{t_{\mathrm{r}}})^{\upsilon}}, & \text{for rising phase} \\ I_0 e^{-(\frac{|t-t_{\max}|}{t_{\mathrm{d}}})^{\upsilon}}, & \text{for decaying phase} \end{cases} \tag{1}$$

where $t_{\max}$ is the time of the maximum intensity (I_0), t_{r} and t_{d} are the rise and decay time constants, and υ is a measure of sharpness of the pulse, referred to as "peakness" by Norris et al.(1996).

Most of the previous statistical studies of the pulse profiles used the peak alignment and averaging method. The statistical profiles generated by this method can illustrate how the average normalised pulse emission varies with the energy. However, both the duration and the fluence of pulses vary significantly. The statistical profiles derived by this method are spiky. They cannot reveal the temporal evolution of pulse emission. In this work, we employ a new pulse-finding method to identify the highest pulse in a given GRB profile, normalize the durations and fluence of such pulses, then study their "statistical" profiles and their "characteristic" profiles by "start-alignment".

It is generally believed that most GRBs, if not all GRBs, are generated at cosmological distances (Mao & Paczyński 1992): their light curves should therefore be stretched by the cosmological time dilation (Piran 1992; Norris et al. 1995). We should therefore expect an anti-correlation between the peak flux and the timescale of the burst. Norris (1995) first reported that the time dilation factor between the bright and dim long bursts is about 2. Che et al. (1997a, b) presented a test to investigate cosmological time dilation in long and short bursts. Their results generally agreed with previous works. In this work, the time dilation effect is examined by studying the pulse duration as a function of the pulse flux.

Li (1996) made an ascending sort by the observed timescale for the GRBs observed by BATSE from April 1991 to September 1994, and divided the bursts into groups according to the observational epoch. He calculated the average burst duration and hardness ratio for each group, then investigated how these measures varied with the observational epoch, and found that the burst durations tend to be shorter in the later epoch groups. This cannot be explained by the present theoretical models. In this work we shall also examine whether or not the pulse durations also have this trend.

In Section 2, we first describe the data, and the methods of noise reduction and background subtraction, then in Section 3 we describe our new pulse-finding algorithm and pulse sample. In Sections 4 and 5, respectively, we present our results of statistical light curves of the highest pulses and their characteristic profiles. The result of an examination of the time dilation effect is presented in Section 6. The temporal evolution of pulse duration is presented in Section 7. The conclusions and a discussion are presented in Section 8.

2 DATA ANALYSIS

The data used for our analysis is the 64 ms temporal resolution and four-channel spectral resolution GRB data observed by BATSE from 1991 April 21 to 1999 January 26. There are 1738 bursts included. It is a concatenation of three standard BATSE data types, DISCLA, PREB, and DISCSC. All these data types are derived from the on-board data stream of BATSE's eight Large Area Detectors (LADs). There are four observing energy channels, with the following approximate boundaries: 25–55 keV, 55–110 keV, 110–320 keV, and >320 keV. The DISCLA data are a continuous stream with 1.024 second resolution. They are independent of burst occurrence and taken as the background. The PREB data cover the interval 2.048 second just prior to a burst trigger.

We make the noise decomposition of the time profiles by the wavelet package analysis technique. It was proven successful in de-noising the original signal and identifying the structure within a burst (e.g., Hurley et al. 1998; Quilligan et al. 1999; Lee et al. 2000). We use DB3 wavelet to make the first-class decomposition with the MATLAB software. The profile is decomposed into a signal component and a noise component.

The method of the background treatment used here is similar to that in Li & Fenimore (1996). Since the DISCLA data are a continuous stream prior to and independent of the burst occurrence, they are always taken as the background. The data of the background is obtained by a linear fitting to the DISCLA data.

3 PULSE-FINDING ALGORITHM AND SAMPLE SELECTION

Many burst time profiles appear to be composed of a series of overlapping pulses, mingled with noise. It is not easy to determine their actual light curves and to isolate a pulse from the time profile. The result of the pulse analysis strongly relies on the algorithms of pulse-finding and sample selection. Several pulse-finding algorithms have been proposed (e.g., Li & Fenimore 1996; Norris et al. 1996; Mitrofanov et al. 1998). Li & Fenimore (1996) suggested an efficacious algorithm to identify a "true peak" from a profile. A "true peak" is not necessarily to be regarded as a pulse. If the profile is composed of only one "true peak", then the "true peak" can be regarded as a pulse. However, most of the profiles are composed of many overlapping "true peaks". It is not easy to identify a pulse in such situations. Norris et al. (1996) introduced a definition of "inseparable pulse". We adopt this concept and regard an "inseparable pulse" as a true pulse. A description of our pulse-finding algorithm now follows.

(1) The peak-finding criterion proposed by Li & Fenimore is $C_{\rm p} - C_{1,2} \geq N_{\rm var}\sqrt{C_{\rm p}}$, where $C_{\rm p}$ (at $t_{\rm p}$) is the maximum count of a candidate peak, $N_{\rm var}$ is an adjustable parameter, typically $3 \leq N_{\rm var} \leq 5$, C_1 and C_2 are, respectively, the photon count at time bin t_1 and t_2, two arbitrary

time bins one before and one after t_p within the candidate peak. If both C_1 and C_2 satisfy the criterion, the candidate peak is regarded as a true peak. This criterion strongly relies on the absolute photon count of the candidate peak. We follow Norris et al. (1996) concept of "inseparable pulse", and then the pulse-finding criterion becomes $1 - C_{1,2}/C_{\rm p} \geq 0.5$. It means that a candidate peak is a true peak only when C_1 (at t_1) and C_2 (at t_2) are lower than the half of the $C_{\rm p}$. With this method, one might find more than one true peak within a burst. We select only the highest one for our analysis.

(2) In order to maintain a high signal-to-noise ratio, we adopt the intensity criterion, $C_{\max} > 10\sigma$, where $C_{\max}$ is the maximum of the pulse, σ the standard deviation of background.

(3) Only those pulses with at least 10 time bins are selected. Those with fewer bins do not provide enough structure information and so are ignored.

We apply the above pulse-finding algorithm to select the highest pulses in the profiles of bursts. We found 760, 885, 885, and 334 such pulses in Channels 1 to 4, respectively. There were 275 bursts, in which the highest pulse could be identified in all four channels. We select these pulses to study the statistical light curves of pulses and their characteristic structures. The duration and amplitude distributions of the highest pulses are shown in Figures 1 and 2, respectively. The pulses identified in channel 3 were used to study the time dilation effect and the evolution of the duration with the observational epoch.

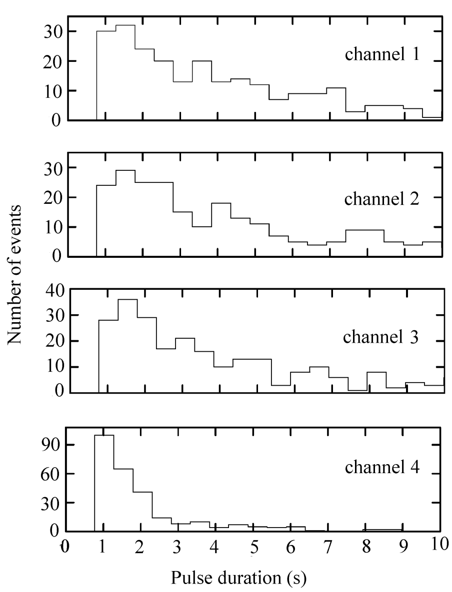

Fig. 1 Distributions of the durations of the highest pulses in four energy channels.

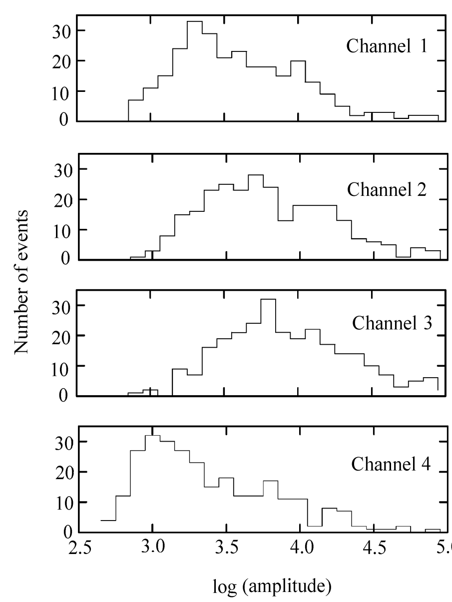

Fig. 2 Distributions of the amplitude of the highest pulses in four energy channels.

4 THE STATISTICAL LIGHT CURVES OF THE HIGHEST PULSE

It was found that the peak-aligned averaged pulse can well illustrate how the average pulse varied with energy. To do that, the time profiles of individual events were averaged by the normalized peak-alignment technique: each profile was normalized by its peak number count

$C_{\max}$, then profiles were then aligned at the peak time bin $t_{\max}$, and then averaged for all the bins along the timescale (e.g., Norris et al. 1996; Mitrofanov et al. 1996; Ramirez–Ruiz & Fenimore 2000). Figure 3 displays the average pulse shape obtained for each of the four energy channels. It was found that they are quite similar to those given by Norris et al.(1996) and Ramirez-Ruiz & Fenimore (2000), although the pulse-finding method and the sample adopted in this paper are somewhat different from the previous works.

It can be seen that the pulse profiles in Figure 3 are spiky. This is mainly caused by the diversity of the durations and the asymmetry of the pulses: much of the diversity and asymmetry would be hidden in the average pulse shapes of Figure 3. Figure 3 illustrates how the average pulse varies with energy, but cannot show how it evolves in time, i.e., the average pulse shapes are not statistical light curves. The statistical light curve should be derived by a start-aligned method: we line up the normalized pulses at the start of the pulse, and then average all time bins. The results are shown in Figure 4. Different from Figure 3, the statistical light curves in Figure 4 not only illustrate the relationship between the timescale and energy, but also show the temporal evolution of the pulse emission in each of the four channels.

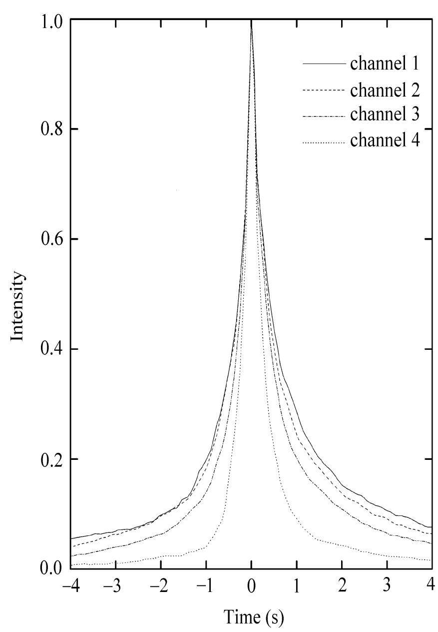

Fig. 3 Average shape of the highest pulses in each of the four energy channels derived by the peak-aligned method.

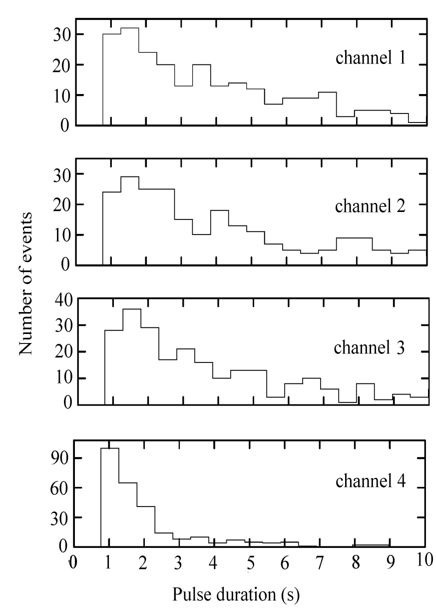

Fig. 4 Statistical light curve of the highest pulses in in each of the four energy channels derived by the start-aligned method.

5 THE CHARACTERISTIC STRUCTURES OF THE HIGHEST PULSES

If one normalizes both the timescale and the amplitude/counts to unity, one can derive the "characteristic" profile of pulse emission. The pulses in GRBs are hypothesized to have the same shape at all energies, differing only by scale factors in time and amplitude/counts ("pulse scale conjecture"). Moreover, the pulses are hypothesized to start at the same time, independent of energy ("pulse start conjecture") (Nemiroff 2000). From the two conjectures, one could expect that the statistical structure of the pulses in the four channels should be the same. We now normalize both the duration and the counts to unity, and obtain the statistical characteristic profiles of pulse emission in the four channels by the start-aligned method. The results are shown in Figure 5. It can be seen that the profiles are the same for all four energy channels. This result supports the two conjectures above and implies that the emission process is similar in the four channels, and that one and the same mechanism is at work at the different energies.

A quantitative expression for the characteristic pulse profile may be useful for theoretical studies. We fitted the profile in Figure 5 to the pulse model proposed by Norris et al. (1996), and obtained the fitting parameters $t_{\rm r}$=0.12, $t_{\rm d}$=0.16, and $\upsilon = 1.09$. The ratio of $t_{\rm r}$ to $t_{\rm d}$ is about 0.75.

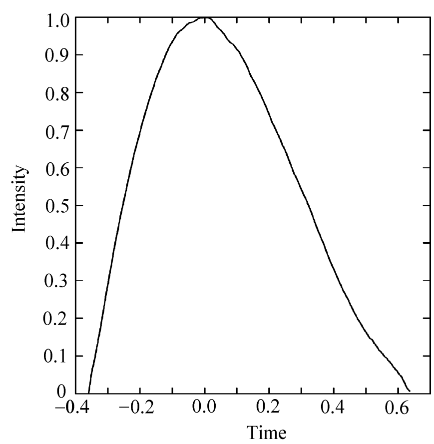

Fig. 5 Characteristic profile of the highest pulses (the same for all four energy channels).

6 THE TIME DILATION EFFECT

It is known that, for sources at redshift z, the observed and intrinsic photon energies, $E_{\rm ob}$ and $E_{\rm in}$, are related by

$$E_{\rm ob} = \frac{E_{\rm in}}{1+z}, \tag{2}$$

and the observed timescale, $T_{\rm ob}$, is related to the proper timescale, $T_{\rm in}$, by

$$T_{\rm ob} = (1+z)T_{\rm in}. \tag{3}$$

Accordingly, one may expect an anti–correlation between burst durations and burst intensities. We examine the correlation between the duration (the FWHM) and the average count within the FWHM of the pulse. The pulses in channel 3 were selected for this purpose. As we mentioned in Section 3, 885 pulses were identified by our pulse–finding algorithm. Some pulses with the same FWHM had different counts, for these we took the average of the counts. Thus, we obtained 128 pairs of pulse durations and average counts. The average count as a function of the FWHM is plotted in the upper panel of Figure 6. A weak anti–correlation between the two can be noticed. For further illustrating of this anti–correlation, we made an ascending sort of the pulse durations, and divided the 128 pairs of FWHMs and average counts into 13 groups. Each group, except the 13th, has 10 pairs. The average FWHM and count in each group were then calculated (the lower panel of Figure 6). Now we can see a significant anti–correlation between the two quantities. A correlation coefficient of 0.70 with a chance probability of 0.009 is obtained through a linear correlation analysis from the Spearman rank correlation method.

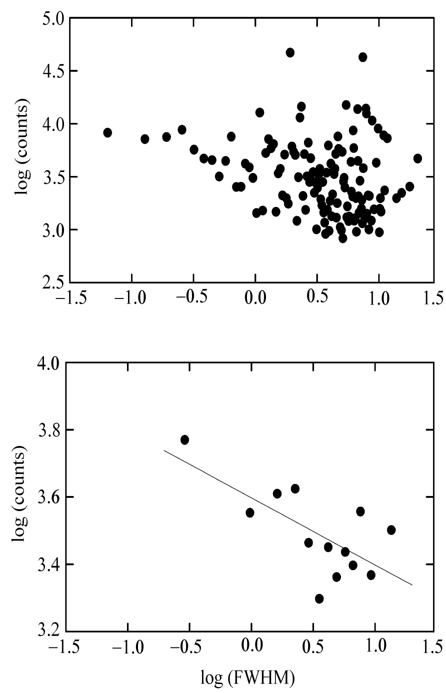

Fig. 6 FWHM - counts plot for the common 128 highest peaks. Upper panel: individual values from channel 3. Lower panel: average values of the above in 13 duration bins. The solid line is the regression line.

7 THE EVOLUTION OF PULSE DURATION WITH OBSERVATIONAL EPOCH

Li (1996) found that the burst duration evolved with the observational epoch: the burst durations tend to be shorter at later times. Do the pulse durations have the similar trend? We selected the pulses in channel 3 for investigating this issue. There were 885 pulses identified by our pulse-finding algorithm in channel 3. The upper panel of Fig. 7 shows the time variation of the monthly average FWHM, and the lower panel, that of the yearly average. The upper panel shows a very weak downward trend, while in the lower panel this trend comes out much more clearly. A linear correlation analysis by Spearman Rank Correlation method gave a linear correlation coefficient of 0.79 with chance probability 0.02.

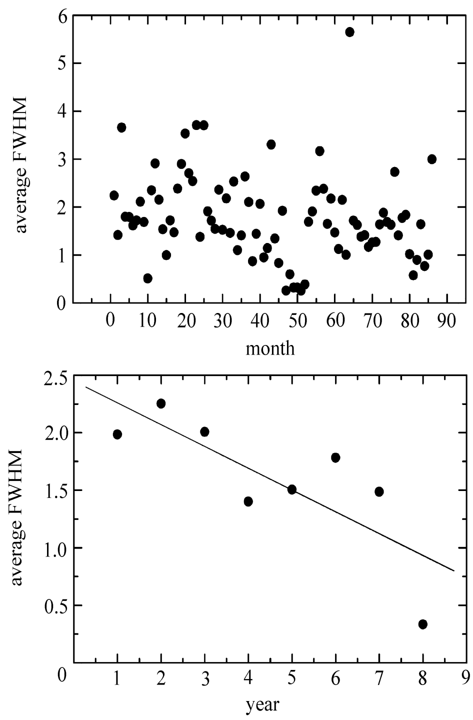

Fig. 7 Time plot of monthly average FWHM of the highest pulses in channel 3 (upper panel) and yearly average FWHM (lower panel).

8 CONCLUSIONS AND DISCUSSION

The statistical properties of the highest pulses in GRBs have been studied. A wavelet package analysis technique and a developed pulse-finding algorithm have been applied to identify the highest pulses from burst profiles observed by BATSE on board CGRO from 1991 April 21 to 1999 January 26. The statistical light curves of the highest pulses in four channels have been derived by an aligning method. These curves illustrate how the pulse emission evolves within the highest pulse. They clearly show that the higher the energy, the narrower the pulse. This is consistent with previous results. By normalizing both the pulse durations and photon counts to unity, the characteristic profiles of the highest pulses in four energy channels are also derived by the same aligning method. They are found to be independent of the pulse duration and the pulse fluence. The result shows that the characteristic profiles in the four channels are almost the same, independent of energy, and strongly supports the previous conclusion that the temporal profiles in different channels are self-similar. This leads to a conjecture that the emission procession of the pulses in different energy bands might be the same. In addition, the cosmological time dilation effect is examined by investigating the relationship between the pulse flux and pulse duration. An anti-correlation between the two quantities is found, which agrees with the expectation of the cosmological time dilation effect. Also, the evolution of pulse duration with the observational epoch is studied. The result shows that the pulse duration is anti-correlated with the observational epoch: the pulse duration tends to be shorter in later observational epochs. The present theoretical model cannot explain this anti-correlation.

The pulses in GRBs are hypothesized to have the same shape at all energies, differing only by scale factors in time and amplitude ("pulse scale conjecture"). Moreover, the pulses are hypothesized to start at the same time, independent of energy ("pulse start conjecture") (Nemiroff 2000). The variation of the pulse duration with the energy is found to be an exponential decay. The statistical light curves of the highest pulses in four energy channels presented in this work not only come to a similar conclusion to previous works—the higher the energy, the narrower the pulse, but also illustrate how the pulse emission evolves within the highest pulses. In previous works, the peak-aligned method was always employed. Inevitably, the statistical pulse shapes derived by this method are spiky and would conceal most of the diversities of the duration and the asymmetry of pulses (note that there are rather wide distributions of the duration and asymmetry of the pulses and these distributions must play a role in the shape derived by the peak-aligned method). They do not reveal the temporal evolution of the pulses. The statistical light curves presented in this work is able to do that. These results confirm the two conjectures of GRB pulses, and may present some clues to theoretical models of pulse emission.

By examining the relation between pulse flux and pulse duration, we obtain a result that is consistent with cosmological time dilation effect: fainter pulses tend to have longer durations. It should be pointed out, however, that the relative time stretching can also be produced by an intrinsic correlation between the duration and the flux. The result in this work cannot distinguish which one of the two factors dominates.

We made a similar analysis as Li (1996) and found that the pulse duration is shorter when observed in later years. While the duration of the whole burst is easily affected by instrumental bias, the duration of the highest pulse within each burst is not. If this effect is true, it will certainly present a great challenge to the current theories. We therefore appeal for other independent investigations.

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