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Intrinsic and Cosmological Signatures in Gamma-Ray Burst Time Profiles: Time Dilation*

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Abstract

The time profiles of many gamma-ray bursts consist of distinct pulses, which offers the possibility of characterizing the temporal structure of these bursts using a relatively small set of pulse shape parameters. We have used a pulse decomposition procedure to analyze the Time-to-Spill (TTS) data for all bursts observed by BATSE up through trigger number 2000, in all energy channels for which TTS data is available. We obtain amplitude, rise and decay timescales, a pulse shape parameter, and the fluences of individual pulses in all of the bursts. We investigate the correlations between brightness measures (amplitude and fluence) and timescale measures (pulse width and separation) which may result from cosmological time dilation of bursts, or from intrinsic properties of burst sources or from selection effects. The effects of selection biases are evaluated through simulations. The correlations between these parameters among pulses within individual bursts give a measure of the intrinsic effects while the correlations among bursts could result both from intrinsic and cosmological effects. We find that timescales tend to be shorter in bursts with higher peak fluxes, as expected from cosmological time dilation effects, but also find that there are non-cosmological effects contributing to this inverse correlation. We find that timescales tend to be longer in bursts with higher total fluences, contrary to what is expected from cosmological effects. We also find that peak fluxes and total fluences of bursts are uncorrelated, indicating that they cannot both be good distance indicators for bursts.

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ABSTRACT

The time profiles of many gamma-ray bursts consist of distinct pulses, which offers the possibility of characterizing the temporal structure of these bursts using a relatively small set of pulse shape parameters. We have used a pulse decomposition procedure to analyze the Time-to-Spill (TTS) data for all bursts observed by BATSE up through trigger number 2000, in all energy channels for which TTS data is available. We obtain amplitude, rise and decay timescales, a pulse shape parameter, and the fluences of individual pulses in all of the bursts. We investigate the correlations between brightness measures (amplitude and fluence) and timescale measures (pulse width and separation) which may result from cosmological time dilation of bursts, or from intrinsic properties of burst sources or from selection effects. The effects of selection biases are evaluated through simulations. The correlations between these parameters among pulses within individual bursts give a measure of the intrinsic effects while the correlations among bursts could result both from intrinsic and cosmological effects. We find that timescales tend to be shorter in bursts with higher peak fluxes, as expected from cosmological time dilation effects, but also find that there are non-cosmological effects contributing to this inverse correlation. We find that timescales tend to be longer in bursts with higher total fluences, contrary to what is expected from cosmological effects. We also find that peak fluxes and total fluences of bursts are uncorrelated, indicating that they cannot both be good distance indicators for bursts.

Subject headings: gamma rays: bursts—cosmology: theory

1. Introduction

Many of the signatures of the cosmological time dilation and the radiation mechanisms of gamma-ray bursts (GRBs) are hidden in the temporal and spectral characteristics of GRBs. The

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subject of this paper is the analysis of the temporal properties of the bursts, and the correlations between intensities and timescales. We use the BATSE Time-to-Spill (TTS) data, which can give much higher time resolution than other forms of BATSE data for most bursts. The advantages and shortcomings of this data, our decomposition of the time profiles into pulses, and the evolution of burst characteristics are described in greater detail in the accompanying paper Lee et al. (2000). What follows is a brief summary. (See also Lee et al. (1996, 1998); Lee (2000).)

Many burst time profiles appear to be composed of a series of discrete, often overlapping, pulses, often with a *fast rise, exponential decay* (FRED) shape (Norris et al. 1996b). The different pulses may represent emission from distinct subevents within the gamma-ray burst source. Therefore, it may be useful to decompose burst time profiles in terms of individual pulses, each of which rises from background to a maximum and then decays back to background levels. We have analyzed gamma-ray burst time profiles by representing them in terms of a finite number of pulses, each of which is described by a small number of parameters.

We have used the phenomological pulse model of Norris et al. (1996b) to decompose gamma-ray burst time profiles into distinct pulses. In this model, each pulse is described by five parameters with the functional form

$$I(t) \;=\; A \exp\left(-\left|\frac{t - t_{\rm max}}{\sigma_{r,d}}\right|^{\nu}\right) , \tag{1}$$

where $t_{\rm max}$ is the time at which the pulse attains its maximum, σ_r and σ_d are the rise and decay times, respectively, A is the pulse amplitude, and ν (the "peakedness") gives the sharpness or smoothness of the pulse at its peak.

We have developed an interactive pulse-fitting program to perform this pulse decomposition on the BATSE TTS data. and used this program to fit pulses to all gamma-ray bursts in the BATSE 3B catalog (Meegan et al. 1996) up to trigger number 2000 in all of the four BATSE LAD energy channels for which TTS data is available and shows time variation beyond the normal Poisson noise for the background. We fit each channel of each burst separately. We have obtained 574 fits for 211 bursts, with a total of 2465 pulses.

In this paper, we focus on the possibility of distinguishing between intrinsic signatures in the temporal characteristics and those which arise from their cosmological distribution. A prominent example of this is the cosmological time dilation effect, which we expect to see since some, and possibly all, gamma-ray bursts originate at cosmological distances.

All timescales in GRBs will be lengthened by a factor of $1 + z$ where z is the redshift of the burst, as a result of cosmological time dilation (Paczyński 1992; Piran 1992). However, this seemingly straightforward test is not simple. First of all, given the great diversity in burst time profiles, it is difficult to decide which timescale is most appropriate for this test. It seems unlikely that any particular timescale is approximately the same in all bursts, so we expect to find time dilation as a statistical effect, rather than for individual bursts.

Secondly, redshifts are known only for a few bursts, so that for the vast majority of bursts we need to use another measure of distance or redshift. Most past analyses have used some measure of apparent GRB brightness for this purpose with the tacit assumption that the corresponding intrinsic brightness is a standard candle or has a very narrow distribution.

The observed apparent brightnesses of bursts are generally measured using either peak fluxes, which give the instantaneous intensity of bursts when they peak, or fluences, which measure the total output of bursts integrated over their entire durations. The brightness measures can also be divided another way, into photon measures and energy measures. Thus, there are several different measures of the apparent brightnesses of bursts. The BATSE burst catalogs give peak photon fluxes and total energy fluences for bursts. The pulse-fitting data presented here can be used to determine count fluxes and count fluences. Most previous work on the evidence for time dilation in burst time profiles has binned the bursts into two or three brightness classes using the peak flux as a measure of brightness, and compared a measure of total burst duration these classes. Use of fluence as a brightness measure has been promoted by Petrosian & Lee (1996a) and Lloyd & Petrosian (1999).

In this paper, we use a number of different timescale and brightness measures. We will describe their correlations using power laws. Although cosmological models generally predict more complex relationships than a simple power law, it would be fruitless to attempt to fit anything more complex than a power law using the pulse-fitting data, which appears to have a large intrinsic scatter. To contrast the cosmological versus the intrinsic signatures, we compare the relations or correlations between strengths and timescales among bursts, which should contain the signatures of cosmological time dilations, with the same correlations among pulses of individual bursts, which can only contain the intrinsic effects. It is likely that some of these correlations are affected by selection effects in our fitting procedures. To investigate the importance of these, we have carried out extensive simulations which are described in the accompanying paper Lee et al. (2000). We use the results of these simulations to test whether or not the correlations we find are properties of the bursts or are products of our procedures. In the next section, we define the various timescales and burst strengths used in this analysis. The correlations relevant to the “time dilation” tests are discussed in Section 3 and the correlations between other quantities within bursts and among bursts are described in Section 4. In Section 5 we discuss the significance of these correlations.

It should be noted that many of the simulated bursts were affected by a truncation that almost never occurred in the actual BATSE TTS data. The TTS data is truncated at 2^{20} counts or 240 seconds, whichever occurs first. In nearly all of the actual bursts, the 240 second limit is reached first, while in many of the the simulated bursts, the 2^{20} count limit is reached first. This truncation can shorten the observed time intervals between the first and last pulses in a burst, and between the two highest amplitude pulses in a burst, but not the observed pulse widths or the observed time intervals between consecutive pulses. *Therefore, all discussions of the first two kinds of time intervals in simulated bursts will only consider simulated bursts where no pulses were truncated by the* 2^{20} *count limit.*

2. Timescales and Intensities

We now describe the characteristics used in our correlation studies and the selection and procedural biases associated with each of them.

2.1. Intensities

We use peak count rates and count fluences as measures of burst intensity or strength. For individual pulses, the peak count rate is given by the amplitude A and the count fluence by

$$\mathcal{F} = A\int_{-\infty}^{\infty} I(t)dt = A\frac{\sigma_r + \sigma_d}{\nu}\Gamma\left(\frac{1}{\nu}\right). \qquad (2)$$

where Γ is the gamma function. For a burst, on the other hand, the peak count rate is $A_{\rm max}$, the largest amplitude of the pulses in the burst, and the total count fluence is $\mathcal{F} = \sum \mathcal{F}_i$, summed over all pulses.

2.2. Time Intervals Between Pulses

The most obvious timescale for individual pulses is the *pulse width*, which is given by

$$T_f = A(\sigma_r + \sigma_d)(-\ln f)^{\frac{1}{\nu}}. \qquad (3)$$

where f is the fraction of the peak height at which the width is measured. and ν is the "peakedness" parameter. In this paper, we use the case $f = 1/2$, for which the width is the full width at half maximum (FWHM). We will discuss the correlations between pulse width and intensity measures in the next section. Here we consider some other timescales, namely the *time intervals between pulses*, which may also be characteristic of the gamma-ray production mechanisms. There are several possible choices of time intervals. We'll examine the *intervals between consecutive pulses* first, which may have the following selection effect: Two pulses with short separations between their peaks may have a large overlap, and thus be identified as only one pulse. This will limit the shortest interval between pulses, introducing a selection bias. On the other hand, when two pulses have a long separation between them, additional smaller pulses may be resolved between them that wouldn't be resolved if the separation were smaller. This will limit the the longest intervals between consecutive pulses, introducing another selection bias.

Figure 1 shows the distributions of the intervals between the peak times $t_{\rm max}$ of adjacent pulses for the simulations and the fits to simulations. It shows that the fitting procedure identifies pulses with longer separations correctly, but misses most pulses with shorter separations.

Figure 2 shows the time intervals between consecutive pulses for bursts with different numbers of pulses, as derived from our fits to the BATSE data and from the simulations. Note that here

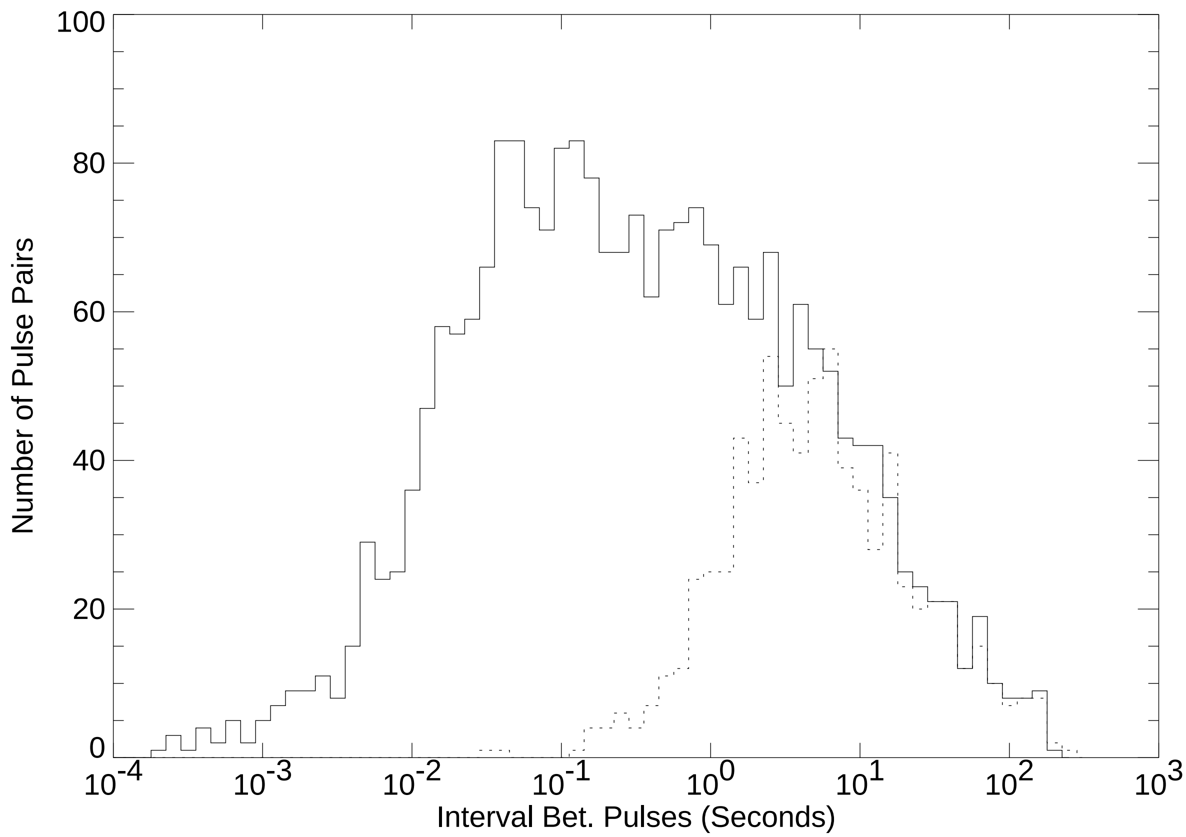

Fig. 1.— Distribution of intervals between peak times of adjacent pulses in initial simulations (solid histogram) and in the results of the fits to the simulated data (dashed histogram). Note that a large number of bursts with small separations are combined with nearby stronger pulses.

and in similar figures to follow, we show only data from channels 2 and 3. In general, channels 1 and 4 show similar behavior, but results from these channels have lower significance because these channels contain fewer pulses. Table 1, columns (a) gives the Spearman rank-order correlation coefficients r_s between these two quantities, and the probabilities that the observed correlations have occured by chance. These show that pulses tend to be closer together in bursts with more pulses, in both the actual bursts, and in the simulated bursts and in the fits to simulated bursts. One selection effect that may contribute to this result in actual bursts is that more complex bursts may simply be bursts with stronger signal-to-noise ratios, which allows more pulses to be resolved within any given time interval. Our analysis of the simulated bursts and the fits to the simulations show similar results. this result is as expected, since pulse peak times were generated independently of each other and of the number of pulses per burst, so more complex bursts will tend to have more pulses in any given time interval. The correlation is weaker for the fits to simulated bursts than for the original simulated bursts because the fitting procedure tends to miss pulses with shorter separations.

Another time interval, *the interval between the peak times of the first and last pulses* in a burst, might be expected to give a good measure of the *total duration* of the burst. However, the determination of this interval can be greatly affected by whether or not low amplitude pulses can be identified above background. This is essentially the same effect as the sensitivity of the T_{90} interval to the signal-to-noise ratios of bursts (Norris 1996; Lee & Petrosian 1997).

Figure 3 and columns (b) of Table 1 compare the number of pulses in each burst with the time interval between the first and last pulses in each burst. They show that the time intervals between the first and last pulse are greater in bursts with more pulses, both in actual bursts, and in simulated bursts and fits to simulated bursts. In actual bursts, this may result from the selection effect described above; more complex bursts may simply have stronger signal-to-noise ratios, making it easier to identify earlier and later pulses. In the simulated bursts and the fits to simulated bursts, this is also as expected since the peak times of pulses were generated independently of the number of pulses in each burst.

A third time interval, the interval *between the peak times of the two highest amplitude pulses* in a burst, may also represent a characteristic time scale for the entire burst. Determination of this interval should be less affected by the selection effects that we have seen with the intervals between consecutive pulses. However, the identification of the two highest pulses may be affected by whether a particular structure in a burst is identified as a single pulse with large amplitude or as multiple overlapping pulses with smaller amplitudes. The interval between the two highest amplitude pulses should be less influenced by the selection effects in the fitting procedure that affect the interval between the first and last pulses in a burst.

Figure 4 and Table 1, columns (c) show the correlations between the number of pulses in each burst and the time intervals between the two highest amplitude pulses in each burst, both for actual bursts, and for simulated bursts and fits to simulated bursts. It appears that unlike the first two

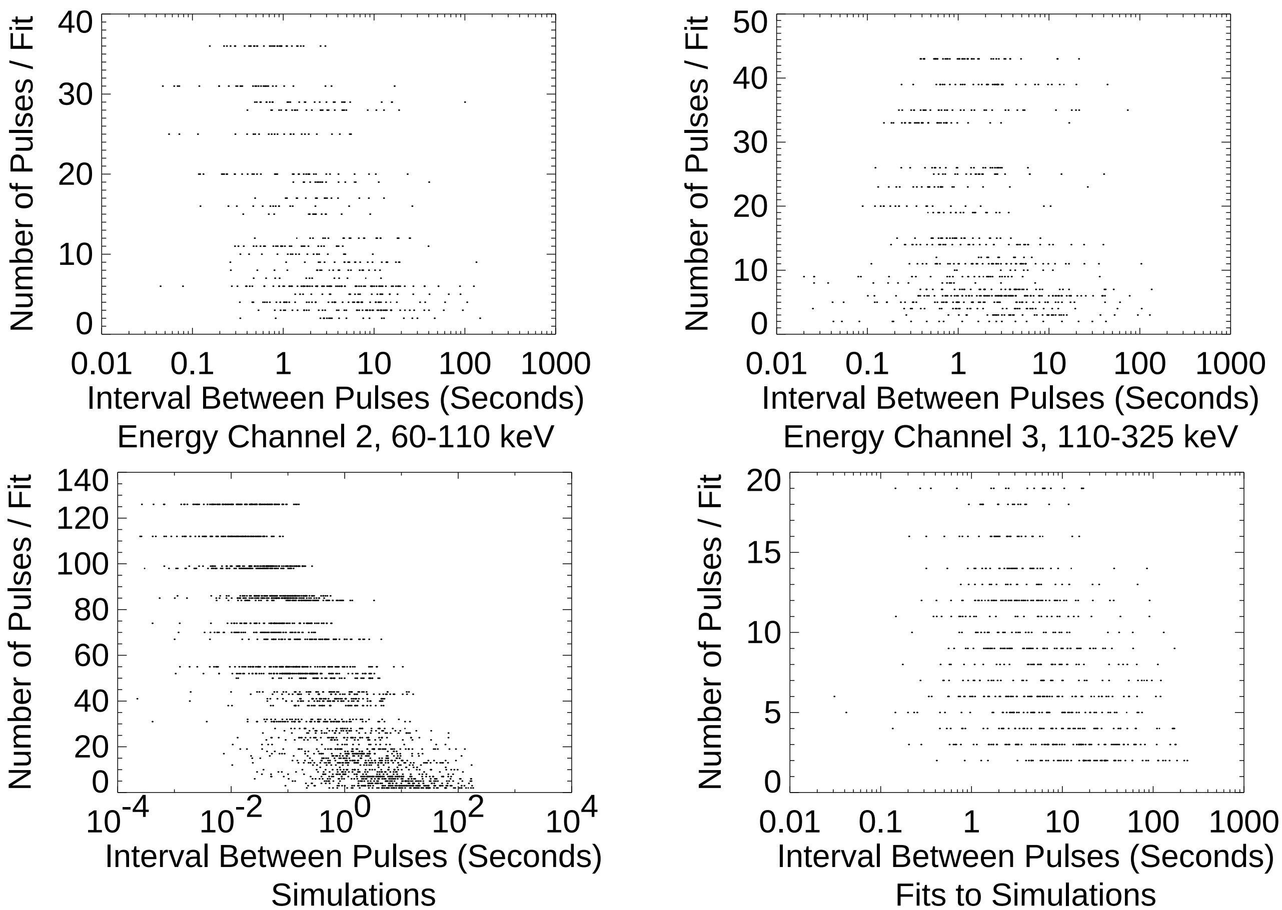

Fig. 2.— Number of pulses per burst versus intervals between adjacent pulses for BATSE energy channels 2 and 3 (upper panels) and for initial simulated bursts and fits to these bursts (lower panels). Similar results were obtained for channels 1 and 4, which have much fewer pulses.

Table 1. Correlation Between Number of Pulses per Burst and Intervals Between (a) Adjacent, (b) First and Last, and (c) Two Highest Amplitude Pulses.

Energy Channel	(a) Adjacent r_s	(a) Adjacent Prob.	(b) First to Last r_s	(b) First to Last Prob.	(c) Two Highest r_s	(c) Two Highest Prob.
1	-0.39	1.8×10^{-14}	0.53	3.6×10^{-8}	-0.07	0.50
2	-0.47	3.0×10^{-33}	0.50	2.7×10^{-8}	-0.12	0.23
3	-0.24	1.6×10^{-10}	0.56	4.4×10^{-11}	0.14	0.13
4	-0.27	8.0×10^{-5}	0.52	0.0013	-0.16	0.35
Sim.	-0.80	0	0.55	1.1×10^{-14}	0.01	0.86
Fits to Sim.	-0.35	6.5×10^{-23}	0.49	6.2×10^{-10}	-0.10	0.22

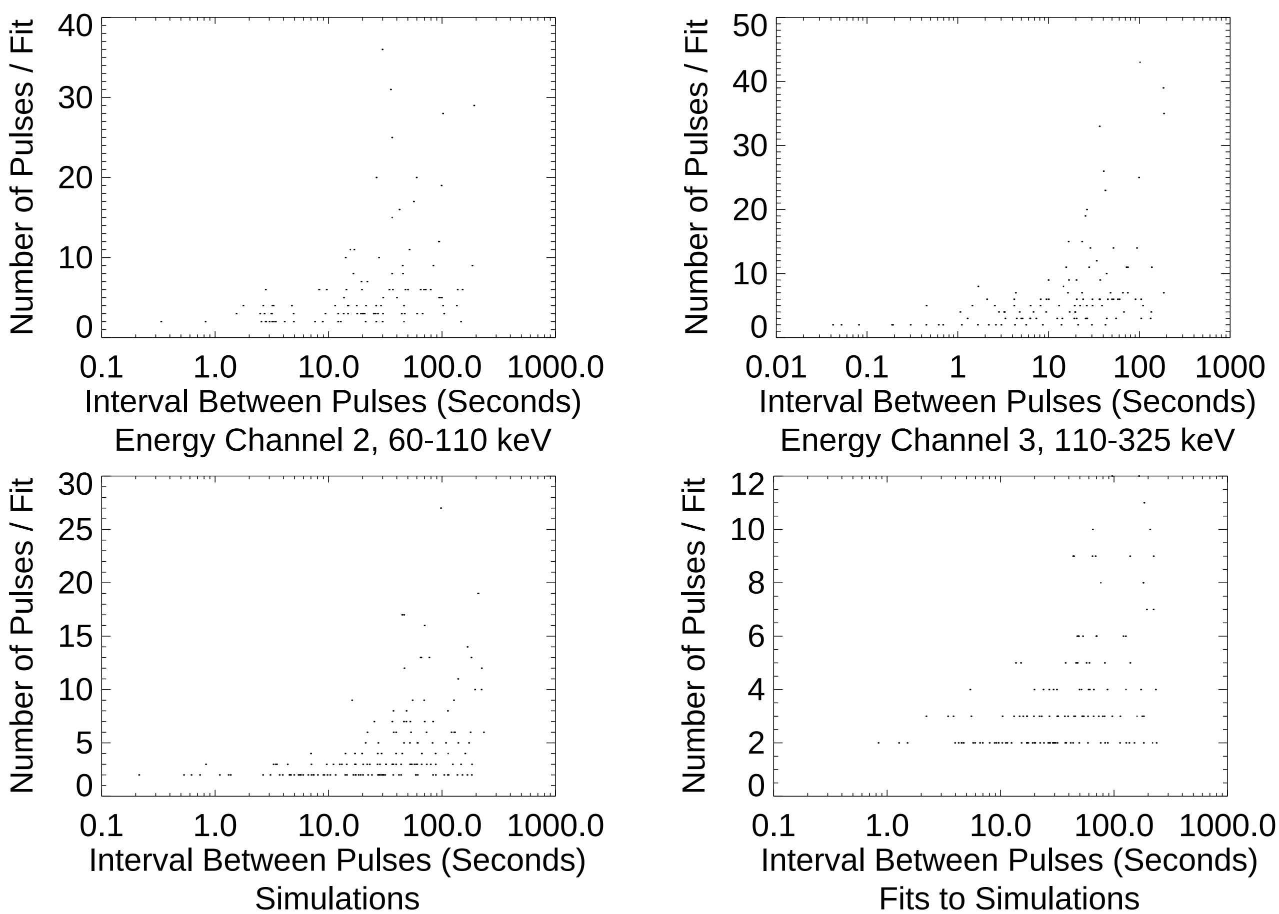

Fig. 3.— Same as Figure 2, except number of pulses per burst versus interval between first and last pulse in each burst.

time intervals described above, there is no tendency for the third time interval to be shorter or longer in bursts with more pulses. This suggests that the interval between the two highest pulses in each fit isn't subject to the signal-to-noise selection effects that affect both the intervals between adjacent pulses and the interval between the first and last pulse in each burst.

The upshot of the above analysis is that the correlations between time intervals and numbers of pulses per burst (or complexity) in the simulated bursts is similar to that of the actual BATSE data, indicating that the simulated data provides a good representation of these aspects of the actual data, and can be used to determine the biases in the data and in the fitting procedure.

3. Time Dilation

We now consider the correlations between timescales and intensities among pulses within bursts and among the bursts to determine the presence of time dilation or time stretching and to test if this is due to cosmological redshift of the sources.

3.1. Peak Luminosity as a Standard Candle

If we assume that the peak luminosities of bursts are approximately a standard candle, then the correlations between pulse amplitudes and timescales can be used to test time dilation. This corresponds to the amplitudes of the constituent pulses in bursts. It has previously been found that higher amplitude pulses have shorter durations (are narrower), (Davis et al. 1994; Norris et al. 1994; Davis 1995), but it has been noted that this could be in part or entirely an intrinsic property of bursters. (Norris et al. 1998). A potential problem with using peak flux as a distance measure for bursts observed by BATSE is that data binned to 64 ms have been typically used, so that the peak fluxes of bursts with sharp spikes may be underestimated. (See Lee & Petrosian (1997).) This should be less of a problem with the variable time resolution TTS data, where the time resolution is inversely proportional to the count rate and every spill represents the same number of counts. The pulse-fitting data from actual BATSE bursts shown in the upper panels of Figure 5 clearly shows that higher amplitude pulses tend to be narrower, or have shorter durations. Table 2 gives the Spearman rank-order correlation coefficients, which show that pulse amplitudes and pulse widths are inversely correlated in all energy channels. The table also gives fitted power laws for pulse amplitude as a function of pulse width. These were obtained by applying the ordinary least squares (OLS) bisector linear regression algorithm (Isobe et al. 1990; Lee 2000).

The lower panels of Figure 5 shows the pulse amplitudes versus pulse width for all pulses in all simulated bursts combined, for the initial simulations and for the fits to the simulations. The fitting procedure tends to miss lower amplitude pulses, but doesn't appear to have strong selection effects in pulse width. However, the fitting procedure introduces an anticorrelation between pulse amplitudes and pulse widths, as shown in the last two rows of Table 2. By design, there is no

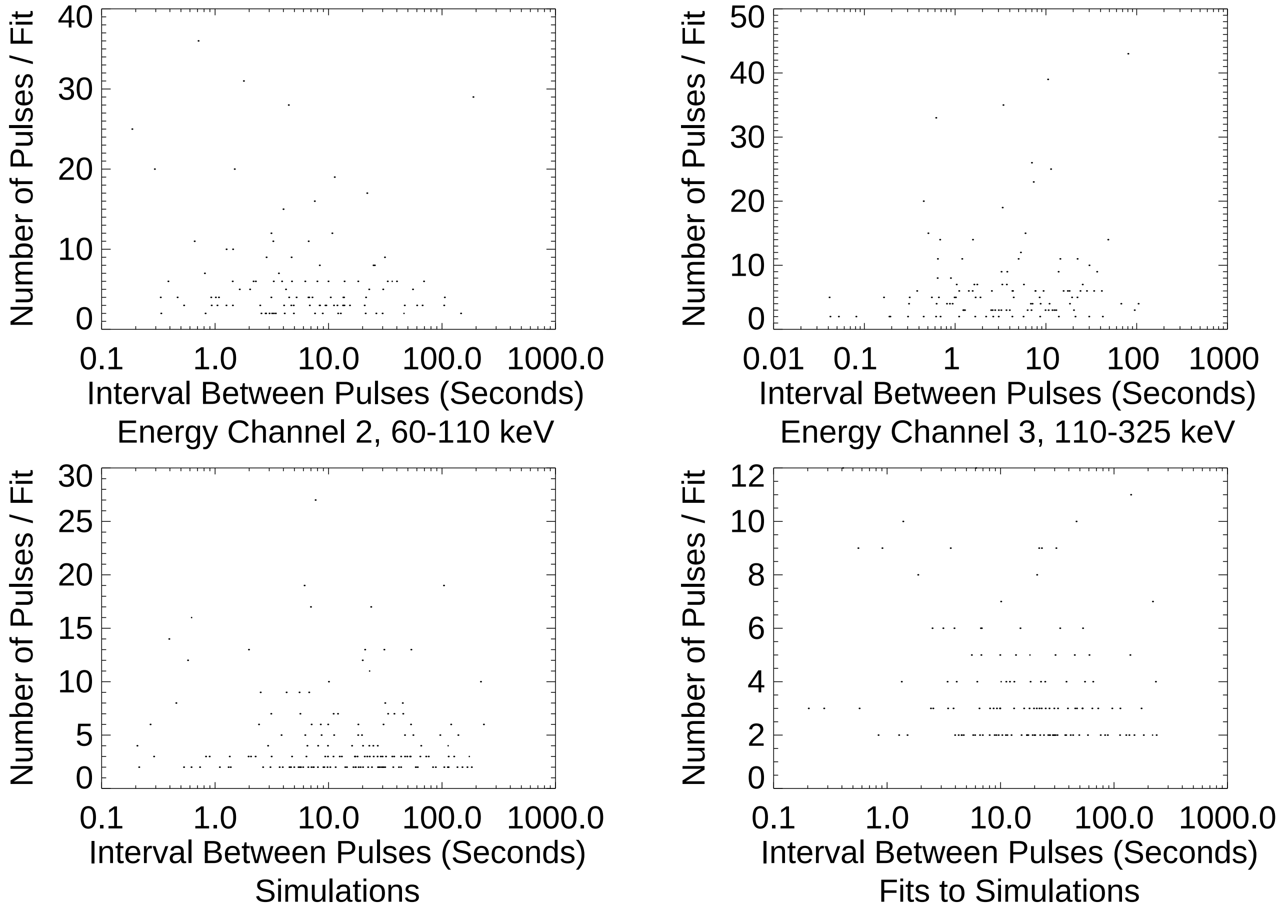

Fig. 4.— Same as Figure 2, except number of pulses per burst versus intervals between two highest amplitude pulses in each burst.

Table 2. Correlation Between Pulse Amplitude and Pulse Width (FWHM) for All Pulses in All Bursts Combined, and the Fitted Power Law Index α.

Energy Channel	r_s	Prob.	α
1	-0.53	9.9×10^{-39}	-0.73 ± 0.03
2	-0.49	0	-0.79 ± 0.02
3	-0.44	1.3×10^{-42}	-0.83 ± 0.02
4	-0.52	2.4×10^{-20}	-0.75 ± 0.03
Simulation	0.0068	0.73	$\cdots$
Fit to Sim.	-0.14	2.1×10^{-6}	$\cdots$

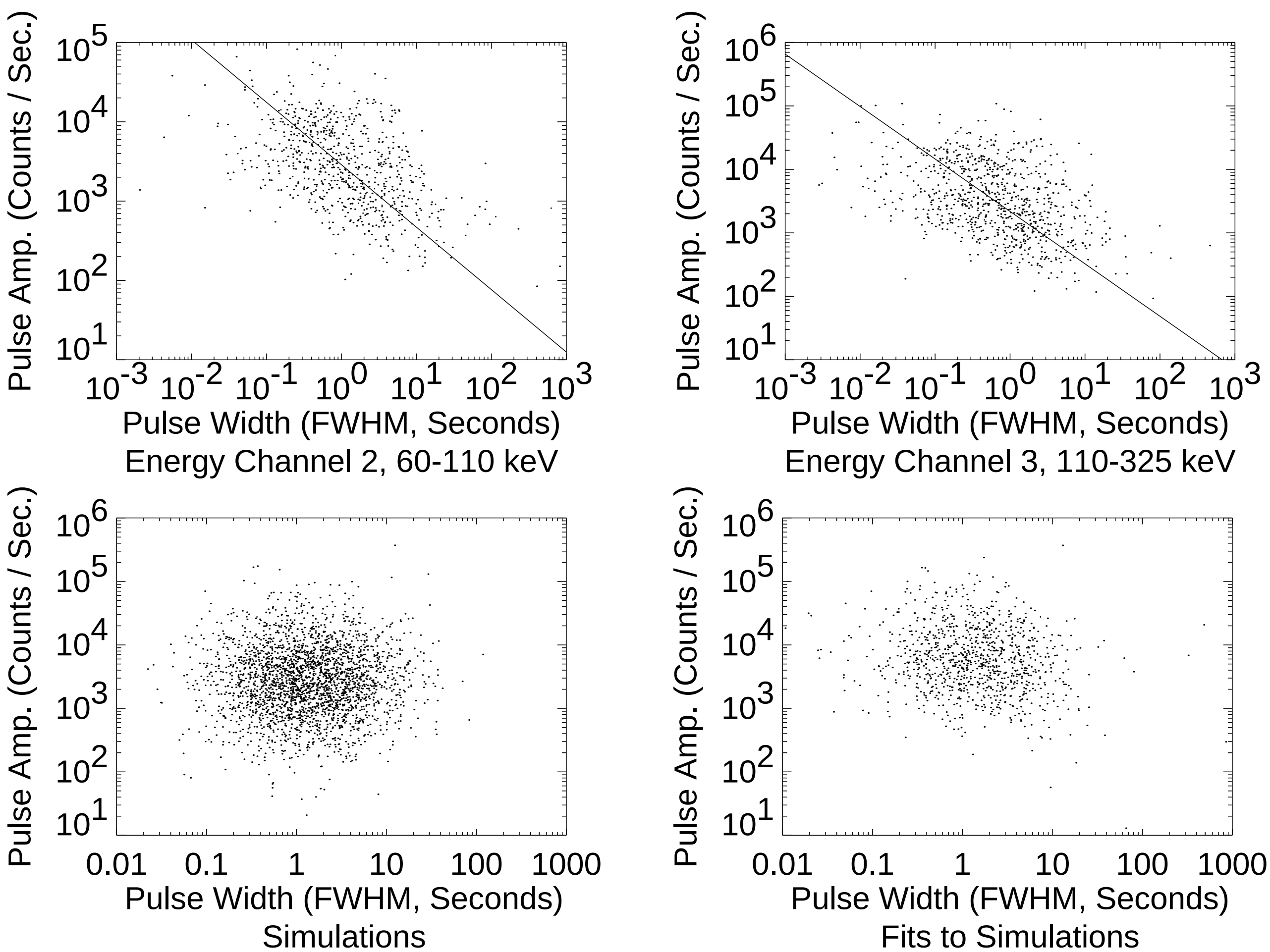

Fig. 5.— Pulse amplitude versus pulse width (FWHM) for all pulses in all bursts combined. The solid lines are obtained from least-squares fits using the OLS bisector method to the logarithms. In the initial simulations and the fits to the simulations (bottom panels), the correlations were insignificant, so no fits were made.

correlation between pulse width and pulse amplitude in the initial simulation, but there is a negative correlation between pulse width and pulse amplitude in the fits to the simulations. However this correlation appear to be weaker and have far less statistical significance than in the fits to actual BATSE bursts.

It is difficult to draw concrete conclusions from the correlations in the combined set of pulses. To distinguish cosmological from intrinsic correlations, we should compare the correlations among bursts and among pulses within individual bursts.

3.2. Cosmological Effects

For testing the first type of correlation, we use the peak fluxes of each of the bursts, *i.e.*, the amplitudes of the highest amplitude pulses, and the widths of the same pulses. These data and their analysis (shown in Figure 6 and columns (a) of Table 3) shows a strong inverse correlation between peak pulse amplitude and pulse width in the actual BATSE bursts, but not in the simulated bursts or the fits to the simulated bursts. This suggests that the correlations observed in the fits to actual bursts observed by BATSE are not caused by selection effects in the fitting procedure, so they may arise from cosmological time dilation, intrinsic properties of the bursters, or selection effects arising from the BATSE triggering criteria.

3.3. Intrinsic Effects

A more unambiguous test of the second type of correlation, intrinsic correlations, can come from analysis of pulse widths and amplitudes of pulses within bursts, because correlations between pulse characteristics within bursts cannot be affected by the distances to the sources, and are less likely to be affected by selection effects due to the triggering process. To this end, we have carried out linear least squares fits to the logarithms of the pulse amplitudes and widths in all actual BATSE bursts, and simulated bursts (before and after fitting) which contain more than one pulse. The results are shown in Table 4, which gives the numbers and fractions of fits that show inverse correlations as determined from the Spearman coefficients, and the probabilities that this would occur by chance if there was no actual correlation, using the binomial distribution. It also gives the distributions of power-law indices (slopes), which we denote as α, in four bins: $\alpha < -1$, $-1 < \alpha < 0$, $0 < \alpha < 1$, and $\alpha > 1$. (For these bins, the results are identical for three different linear regression methods that are symmetric in the two variables being compared. See Isobe et al. (1990); Lee (2000).) The last column of Table 4 gives the median power law index from the OLS bisector method. For all energy channels, a significant majority of fits show inverse correlations between pulse widths and pulse amplitudes *within* bursts. When we examine the actual BATSE bursts for which the rank correlations have the greatest statistical significance, shown in the upper panels of Figure 7, we find that the vast majority of these show inverse correlations between pulse

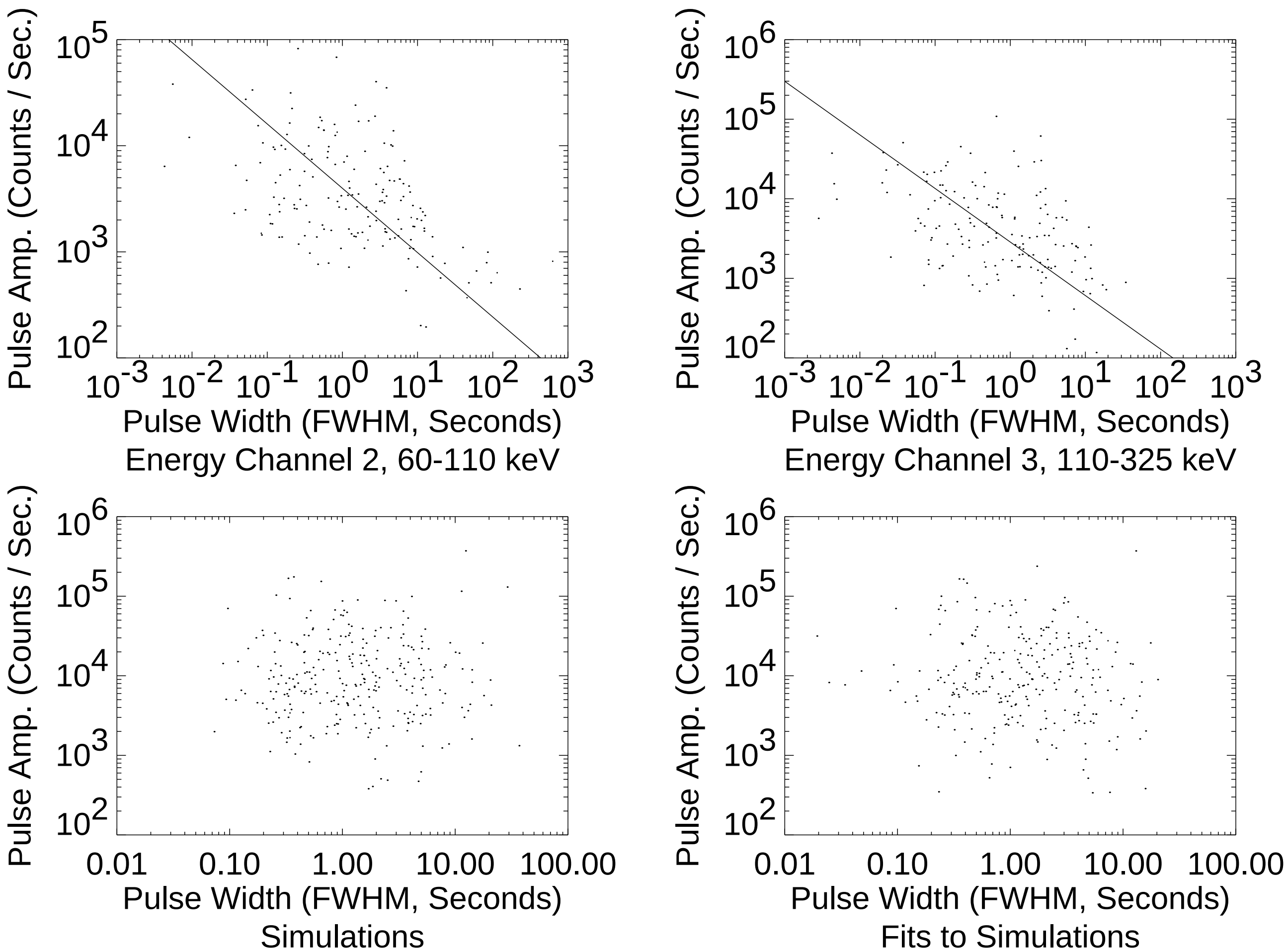

Fig. 6.— Same as Figure 5, except for the highest amplitude pulse in each burst.

widths and pulse amplitudes; in the bursts where the correlations are positive, the correlations also tend to be less statistically significant. The pulse amplitudes most often vary as a small negative power of the pulse width. The power law indices are significantly different from those relating pulse amplitude to pulse width for the highest amplitude pulses in each burst (Petrosian et al. 1999). Ramirez-Ruiz & Fenimore (1999) found similar results for the sample of 28 complex bursts fitted by Norris et al. (1996b). As noted by those authors, this anticorrelation could be consistent with internal shock models of GRBs.

Because of the possible far-reaching effects of this result, it is important to ensure that this is not due to a selection or analysis bias. Our simulations can to some degree answer this question. Table 4 also shows that there are no correlations amplitude and pulse width within the simulated bursts. In the fits to the simulations, however, more bursts show a negative correlation between pulse amplitude and pulse width than show a positive correlation. This asymmetry appears to be as large as it is for the fits to actual BATSE data, which would suggest that the observed tendency for higher amplitude pulses within bursts to be narrower arises largely from a selection effect in the pulse-fitting procedure. However, when we compare the fits to actual and simulated bursts for which the rank correlations have the greatest statistical significance, shown in the lower panels of Figure 7, we find a different result. In the simulated data, in the bursts with correlations between pulse widths and pulse amplitudes with higher statistical significance, the fraction that have positive correlations between pulse widths and pulse amplitudes is similar to that in bursts where the rank correlations have weaker statistical significance; the asymmetry doesn't depend on the statistical significance of the correlations. This is unlike the fits to actual bursts, where almost all of the bursts with the most statistically significant correlations show a negative slope (Petrosian et al. 1999). Therefore, the observed inverse correlations between pulse widths and pulse amplitudes within actual bursts appear to arise in part from intrinsic properties of the sources.

However, some caution is necessary in the interpretation of these results. This is because we find correlations between the errors in the fitted pulse parameters by comparing the parameters used in the simulations with those obtained from the fits to the simulations. For simulated bursts consisting of a single pulse in both the original simulation and in the fit, the identification of pulses between the simulation and the fit is unambiguous and unaffected by the effects of missing pulses. Figure 8 shows that the errors in the fitted pulse amplitudes and the fitted pulse widths tend to have an inverse correlation; when the fitted amplitude is larger than the original amplitude, the fitted width tends to be smaller than the original width, and vice versa. The same effect also appears when we compare the highest amplitude pulses from all bursts, or all pulses matched between the simulations and the fits to the simulations. This selection effect may cause weak inverse correlations between pulse amplitude and pulse width within fits to actual or simulated bursts, so it may be another reason why a large majority of both actual BATSE bursts and fits to simulated bursts show an inverse correlation between pulse amplitude and pulse width within the bursts, as found here and by Ramirez-Ruiz & Fenimore (1999). *However, we conclude that the evidence for intrinsic correlation between pulse amplitude and width is weak and requires further study. Therefore, caution*

Table 3. Correlation Between Highest Pulse Amplitude and (a) Width of Highest Amplitude Pulse and (b) Interval Between Two Highest Pulses in Each Burst, and the Fitted Power Law Index α.

Energy Channel	(a) Pulse Width r_s	Prob.	α	(b) Interval r_s	Prob.	α
1	-0.57	9.1×10^{-15}	-0.60 ± 0.05	-0.42	2.7×10^{-5}	-0.86 ± 0.06
2	-0.52	5.8×10^{-14}	-0.61 ± 0.04	-0.42	7.2×10^{-6}	-0.91 ± 0.06
3	-0.51	1.1×10^{-12}	-0.67 ± 0.05	-0.34	1.8×10^{-4}	-0.83 ± 0.06
4	-0.71	7.1×10^{-12}	-0.64 ± 0.05	-0.40	0.017	-0.82 ± 0.11
Sim.	0.0059	0.92	···	0.03	0.74	···
Fit to Sim.	-0.075	0.20	···	-0.01	0.93	···

Table 4. Correlations Between Pulse Amplitude and Pulse Width Within Bursts, and the Distributions and Medians of the Fitted Power Law Index α.

Energy Channel	% Neg. Corr.	Binom. Prob.	$\alpha < -1$	$-1 < \alpha < 0$	$0 < \alpha < 1$	$\alpha > 1$	Med. α
1	$65/94 = 69\%$	0.00020	21	42	22	9	-0.37
2	$74/109 = 68\%$	0.00019	21	58	21	9	-0.43
3	$82.5/116 = 71\%$	5.4×10^{-6}	17	63	21	15	-0.46
4	$26.5/35 = 76\%$	0.0023	3	26	5	1	-0.55
Sim.	$104.5/223 = 47\%$	0.35	39	55	65	64	0.55
Fit to Sim.	$126.5/198 = 64\%$	9.3×10^{-5}	32	86	53	24	-0.39

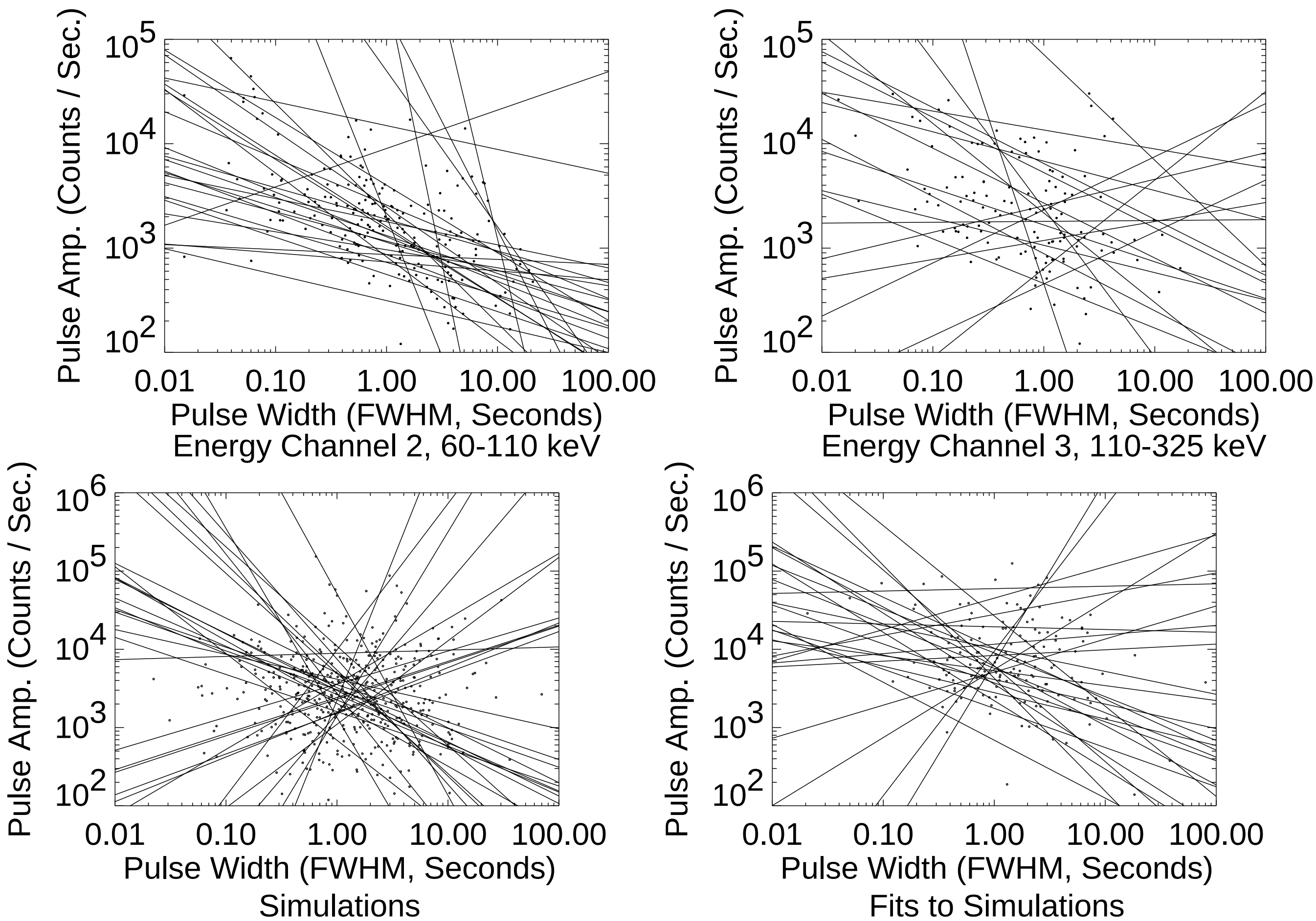

Fig. 7.— Pulse amplitudes versus pulse widths within bursts for bursts with strongest correlations. The lines show the fitted power law indices to pulses in individual bursts with strong correlations. Note that in the BATSE bursts (upper panels), a large majority of the bursts show negative correlations (or slopes) while in the simulations (lower panels), the numbers with positive and negative correlations or slopes are much closer to equal.

should be exercised in the interpretation of this result, in particular in using it as evidence against the external shock model.

3.4. Other Timescales

Cosmological time dilation must affect all timescales within bursts, not only pulse widths. Some of these timescales may provide a more robust test of cosmological time dilation. This is because use of a pulse width as a burst duration is subject to the following uncertainty. Because of the spectral shift due to cosmological redshift, for the dimmer, hence more distant, bursts, BATSE will be detecting higher energy rest frame photons. gamma-rays were originally produced at higher energies but had redshifted to lower energies when they were detected. Since both burst durations (Fenimore et al. 1995) and pulses (Lee et al. 2000) tend to be shorter at higher energies, this would weaken the correlations between amplitude and width due to time dilation.

We have seen earlier that the *intervals between the peak times* of the two highest amplitude pulses in each burst do not appear to increase or decrease with energy, so that cosmological redshift of photon energies should not affect these intervals. As shown in the upper panels of Figure 9 and columns (b) of Table 3, these intervals also show a significant inverse correlation with the amplitudes of the highest amplitude pulses in the actual bursts, so they are shorter for brighter bursts.

Such a trend does not seem to be present in the fits to the simulated data, and is not present in the initial simulated data by design (See Figure 9, lower panels, and bottom two rows of Table 3, columns (b).) The distributions are very similar for the simulated bursts and for the fits to the simulations, although the fits to simulations tend to miss points when both the peak amplitudes and the intervals between the two highest amplitude pulses are small. Therefore, it appears that the correlations observed in the fits to actual bursts observed by BATSE are not caused by selection effects in the fitting procedure, but may arise from cosmological time dilation or from intrinsic properties of the bursts. An early study of time dilation using the intervals between pulses found inconsistent results (Neubauer & Schaefer 1996), but a number for later studies have found evidence of time dilation (Norris et al. 1996a; Deng & Schaefer 1998a,b) consistent with our results.

To see if some kind of correlation is present among pulses within bursts, we compare pulse amplitudes with time intervals between pulses within bursts as follows: For each burst time profile consisting of three or more pulses, we order the individual pulses by decreasing pulse amplitude. Then we look for correlations between the amplitude of each pulse and the absolute value of the intervals between it and the pulse with the next lower amplitude. The results are shown in Table 5. There appears to be a more frequent occurrence of inverse correlations than positive correlations between pulse amplitudes and intervals between pulses within bursts in the BATSE data, but this is statistically insignificant in all energy channels except possibly channel 1. This table also shows that the fitting procedure does not introduce any significant bias.

Finally, it should also be noted that the fitted power law indices for highest pulse amplitude

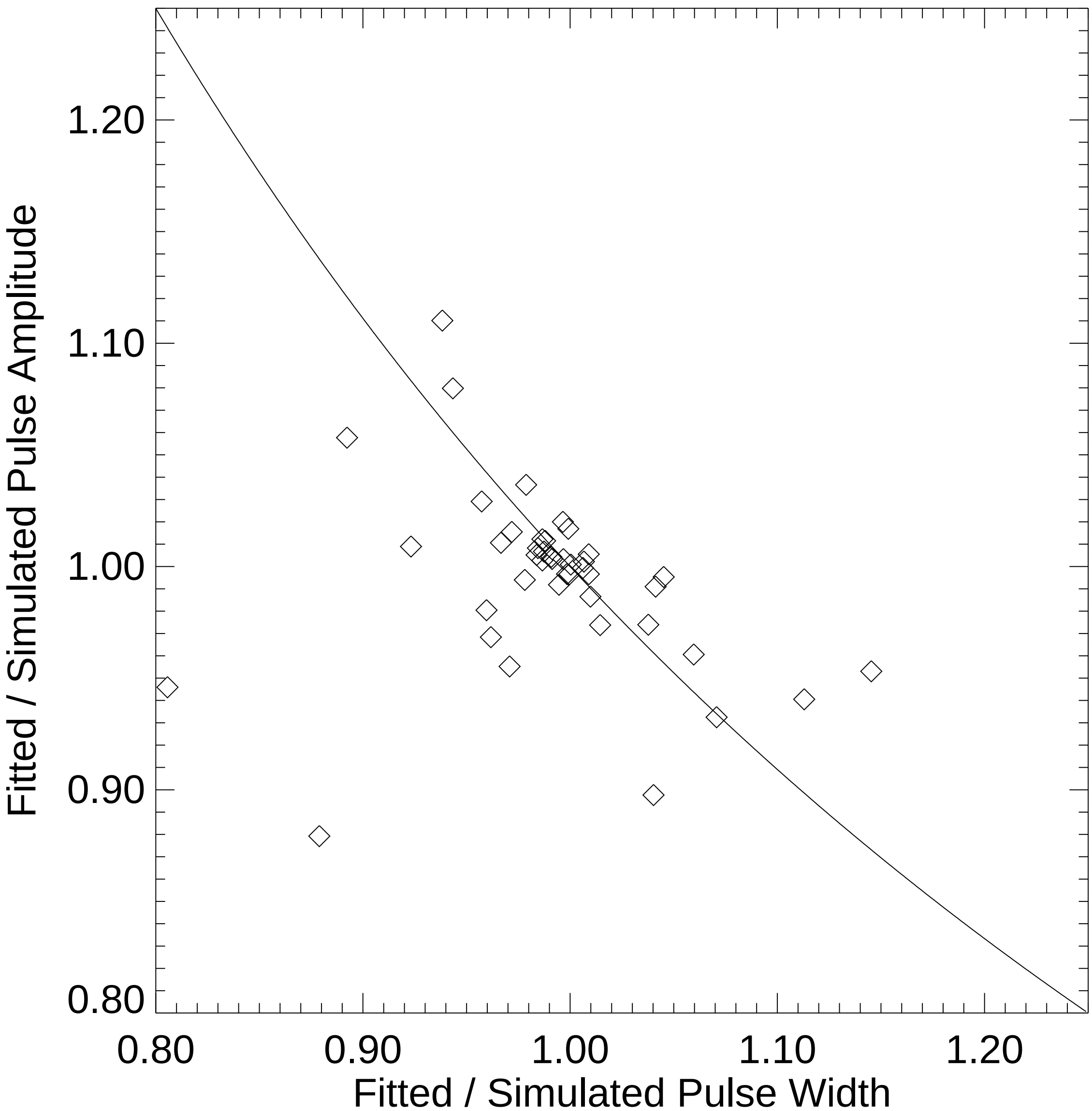

Fig. 8.— Ratios of fitted to simulated pulse amplitudes versus ratios of fitted to simulated pulse widths, with line of constant count fluence, for single-pulse simulated bursts. Note that the errors arising from the fitting procedure for these quantities are anticorrelated, which would cause a bias in the fitting procedure favoring anticorrelated pulse amplitudes and pulse widths.

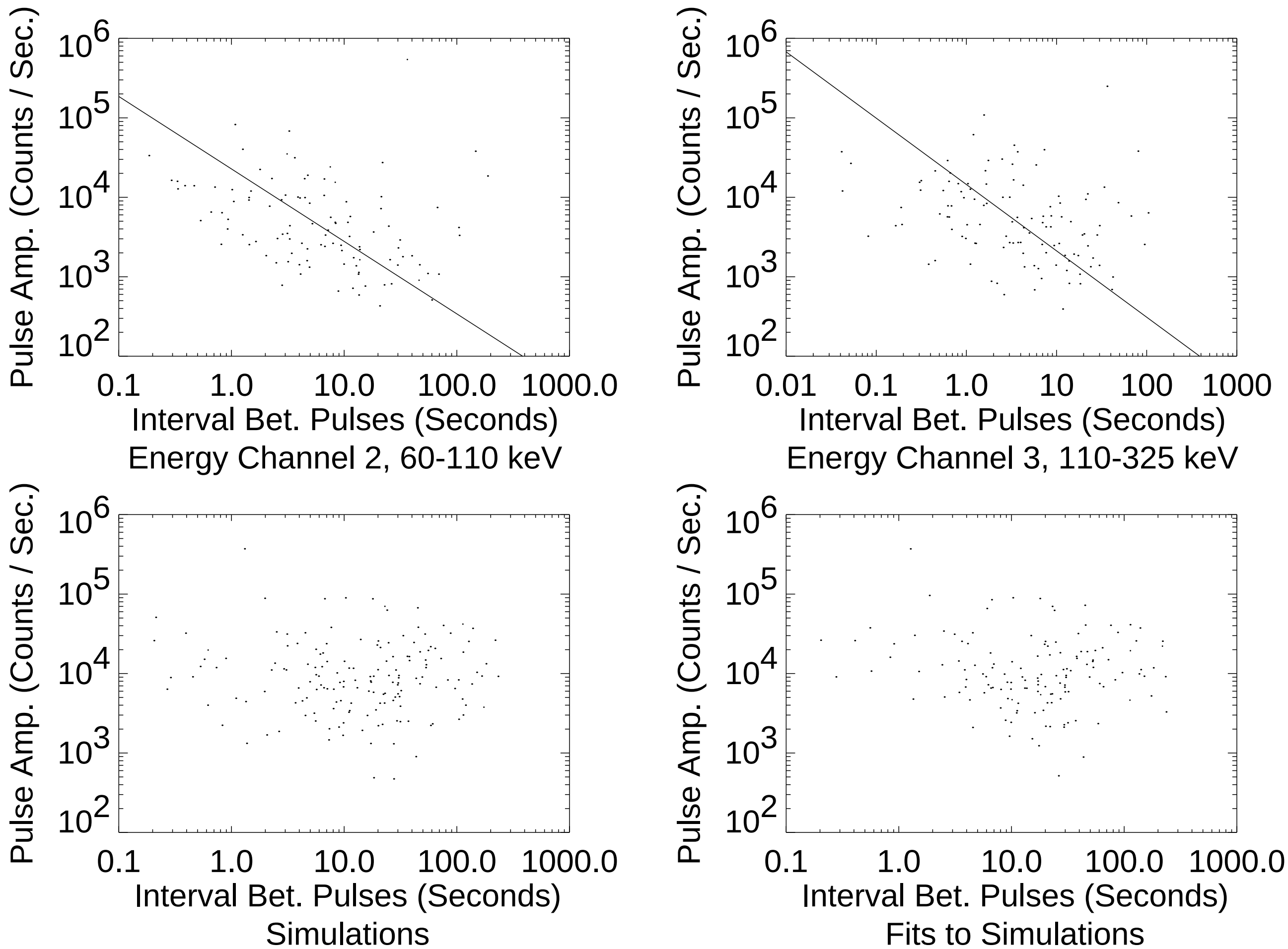

Fig. 9.— Highest pulse amplitude versus interval between two highest amplitude pulses in each burst. In the initial simulations and the fits to the simulations (bottom panels), the correlations were insignificant, so no fits were made.

versus width of the highest amplitude pulse are smaller than -1, which is inconsistent with purely cosmological effects. For a given variation in the highest pulse amplitude, the corresponding variation in pulse width is too great to be accounted for by only cosmological time dilation. We have also seen that within individual bursts, higher amplitude pulses have a strong tendency to be narrower, which must result from intrinsic properties of the GRB sources themselves. It seems likely that the observed correlation between the highest pulse amplitude and the width of the highest pulses in each burst could result from a combination of cosmological and non-cosmological effects.

One of the possible intrinsic effects that could contribute to the inverse correlations of pulse widths with pulse amplitudes is that the total energy in a burst, or within individual pulses, might tend to fall within a limited range, or might have an upper limit. This would be the case if, for example, the fluence of a burst were a better measure of distance than the peak flux. In the next section, we repeat the above tests using the fluence instead of peak flux as a measure of the strengths of bursts and pulses.

On the other hand, the power law indices for highest pulse amplitude versus the time interval between the peaks of the two highest pulses in each burst may be consistent with the expected results of cosmological time dilation alone. Furthermore, it seems likely that this correlation is less affected by intrinsic properties of bursters or by selection effects than the correlation between the highest pulse amplitude and the width of the same pulse in each burst. For example, if the range of radiated energy in entire bursts or in individual pulses, were limited by the production mechanism, or by selection effects, this would be far less likely to affect intervals between pulses than to affect pulse widths.

3.5. Integrated Luminosity as a Standard Candle

Petrosian & Lee (1996a) have suggested that the integrated luminosities of bursts, measured using either energies or photons, are likely to be better standard candles than their peak luminosities. This would be the case if the total energy output of bursters fall in a narrow range of values, and much of the variation in flux results from the broad range of burst durations. Petrosian & Lee (1996b); Lee & Petrosian (1997) have also found that the energy fluences of bursts and their durations show a positive correlation, which is the opposite of what cosmological time dilation should cause. In what follows we carry out similar tests for bursts and for pulses within individual bursts. We shall see that the count fluences of bursts and pulse widths show a positive correlation, while the count fluences of bursts and time intervals between pulses show no correlation, and neither of these effects can arise from cosmological effects. However, determining the significance of some of these correlations is difficult because the simulated bursts were generated with no correlations between pulse width and pulse amplitude, and therefore have a positive correlation between pulse width and pulse count fluence.

In Figure 10, we show that the pulse widths of the highest amplitude pulses have positive correlations with the total count fluences of each fit that appear to be significant in all energy channels except perhaps in channel 3. (See also Table 6, columns (a).) The positive correlation appears somewhat stronger in the fits to simulations than in the simulations. As mentioned above, this makes the interpretation of this result difficult.

Correlations between pulse width and pulse count fluence *within* bursts do not appear to have been studied before. In Table 7, we show the distribution and some moments of the power law index β, which is obtained from linear fits to the logarithms of the fluence and widths of pulses in individual bursts. As evident, a significant majority of fits in all energy channels and in the simulations show strong positive correlations between pulse width and pulse count fluence within individual bursts. (See Table 7 and the upper panels of Figure 11.) Pulse count fluences most often vary as a large positive power of the pulse width. (Because more bursts have $|\beta| > 1$ than $|\beta| < 1$, taking the median of the reciprocal of β is more appropriate.)

The last two rows of Table 7 and the lower panels of Figure 11 show that the correlations in the fits to simulations are similar, though somewhat weaker in the original simulations, so that the observed correlation for the BATSE bursts is probably not a result of the fitting procedure.

Figure 12 shows that there are no significant correlations between the errors in the fitted count fluences and the fitted pulse widths for simulated bursts consisting of a single pulse in both the simulation and the fit. Therefore, the uncorrelated errors in the pulse count fluences and pulse widths would tend to smear out any existing correlations rather than to create correlations, which is what we have seen above.

The relation between the total count fluence and time interval between the two highest amplitude pulses in the actual and simulated bursts are shown in Figure 13 and columns (b) of Table 6.) The two quantities have positive correlations in all energy channels in the actual BATSE bursts, as determined from the Spearman rank-order correlation coefficients. However, the correlation is statistically insignificant in all channels, except perhaps in channel 3.

The distributions of the total burst count fluence versus *the intervals between the peak times* of the two highest amplitude pulses in each burst are very similar for the simulated bursts and for the fits to the simulations, although the fits to simulations tend to miss points when the intervals between the two highest amplitude pulses are small. However, columns (b) of Table 6 show no significant correlation for either the simulations or the fits to the simulations. This indicates that any correlation that may be present in the BATSE bursts is intrinsic to the radiative process.

We can also compare the count fluences of individual pulses with the time intervals between pulses within bursts. The results, shown in Table 8, show no statistically significant correlations between these two quantities. The simulations and fits to simulations also show no statistically significant correlations.

In summary, all correlations between *pulse* count fluences and pulse widths are positive, and probably result from the simple fact that pulses of longer duration tend to contain more counts.

Table 5. Correlations Between Pulse Amplitude and Intervals Between Pulses Within Bursts, and Distributions and Medians of the Fitted Power Law Index α.

Energy Channel	% Neg. Corr.	Binom. Prob.	$\alpha < -1$	$-1 < \alpha < 0$	$0 < \alpha < 1$	$\alpha > 1$	Med. α
1	$42/62 = 68\%$	0.0052	5	38	14	5	-0.47
2	$54/89 = 61\%$	0.044	9	49	26	5	-0.44
3	$55/95 = 58\%$	0.12	4	51	34	6	-0.32
4	$17.5/24 = 73\%$	0.064	2	15	5	2	-0.48
Sim.	$44/156 = 51\%$	0.11	23	43	52	38	0.67
Fit to Sim.	$74/132 = 56\%$	0.16	17	60	34	21	-0.29

Table 6. Correlation Between Total Count Fluence and (a) Pulse Width (FWHM) of Highest Amplitude Pulse in Each Burst and (b) Interval Between Two Highest Pulses in Each Burst, and the Fitted Power Law Index β.

Energy		(a) Pulse Width			(b) Interval	
Channel	r_s	Prob.	α	r_s	Prob.	α
1	0.29	2.4×10^{-4}	0.89 ± 0.06	0.096	0.36	0.99 ± 0.03
2	0.27	2.7×10^{-4}	0.91 ± 0.05	0.15	0.11	1.03 ± 0.06
3	0.17	0.023	0.93 ± 0.04	0.26	4.5×10^{-3}	0.98 ± 0.06
4	0.33	5.8×10^{-3}	0.95 ± 0.05	0.25	0.15	1.09 ± 0.10
Simulation	0.23	8.9×10^{-5}	1.42 ± 0.18	-0.04	0.59	...
Fit to Sim.	0.33	1.3×10^{-8}	1.30 ± 0.17	-0.06	0.51	...

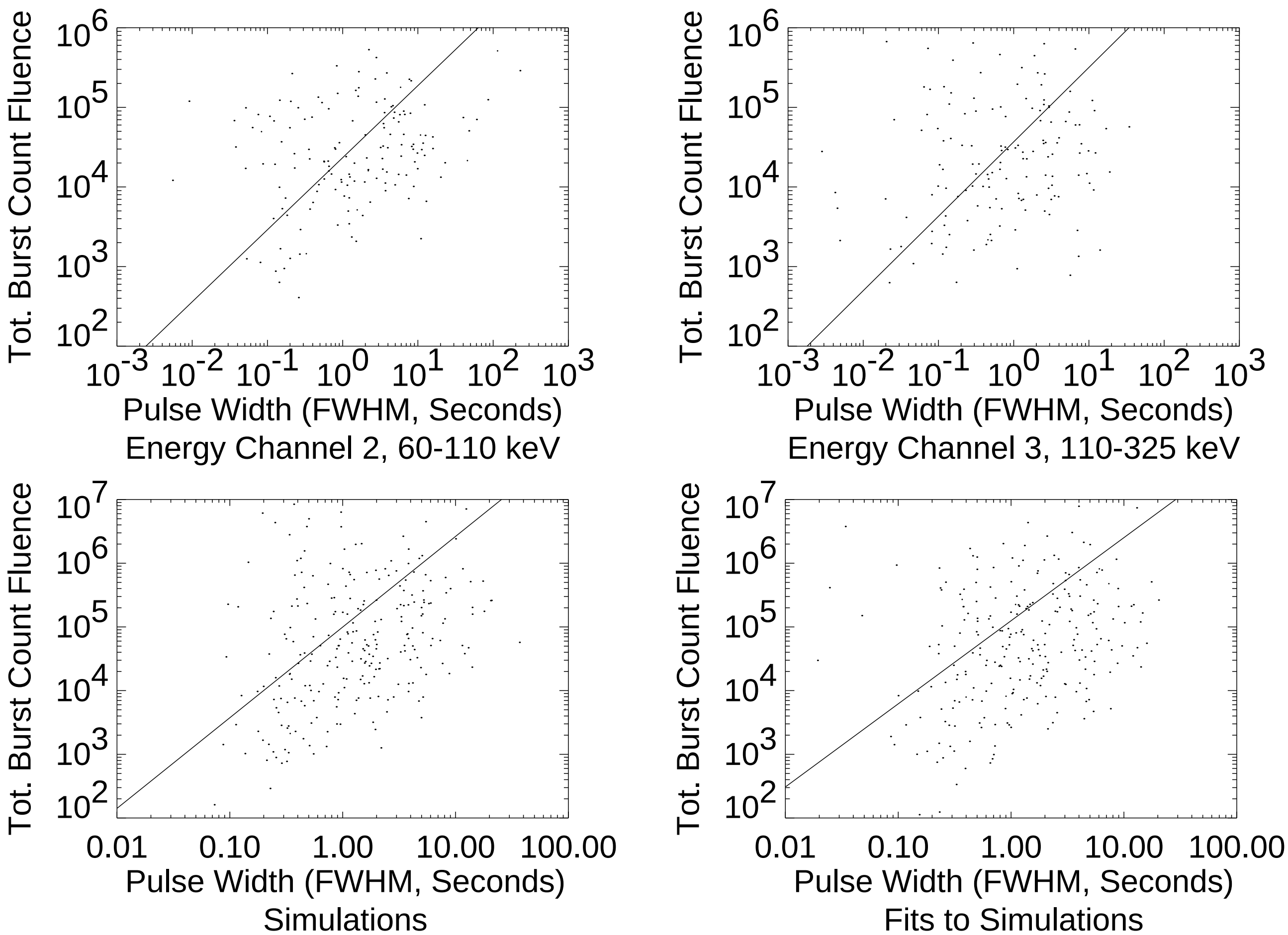

Fig. 10.— Total count fluence versus pulse width (FWHM) of highest amplitude pulse in each burst.

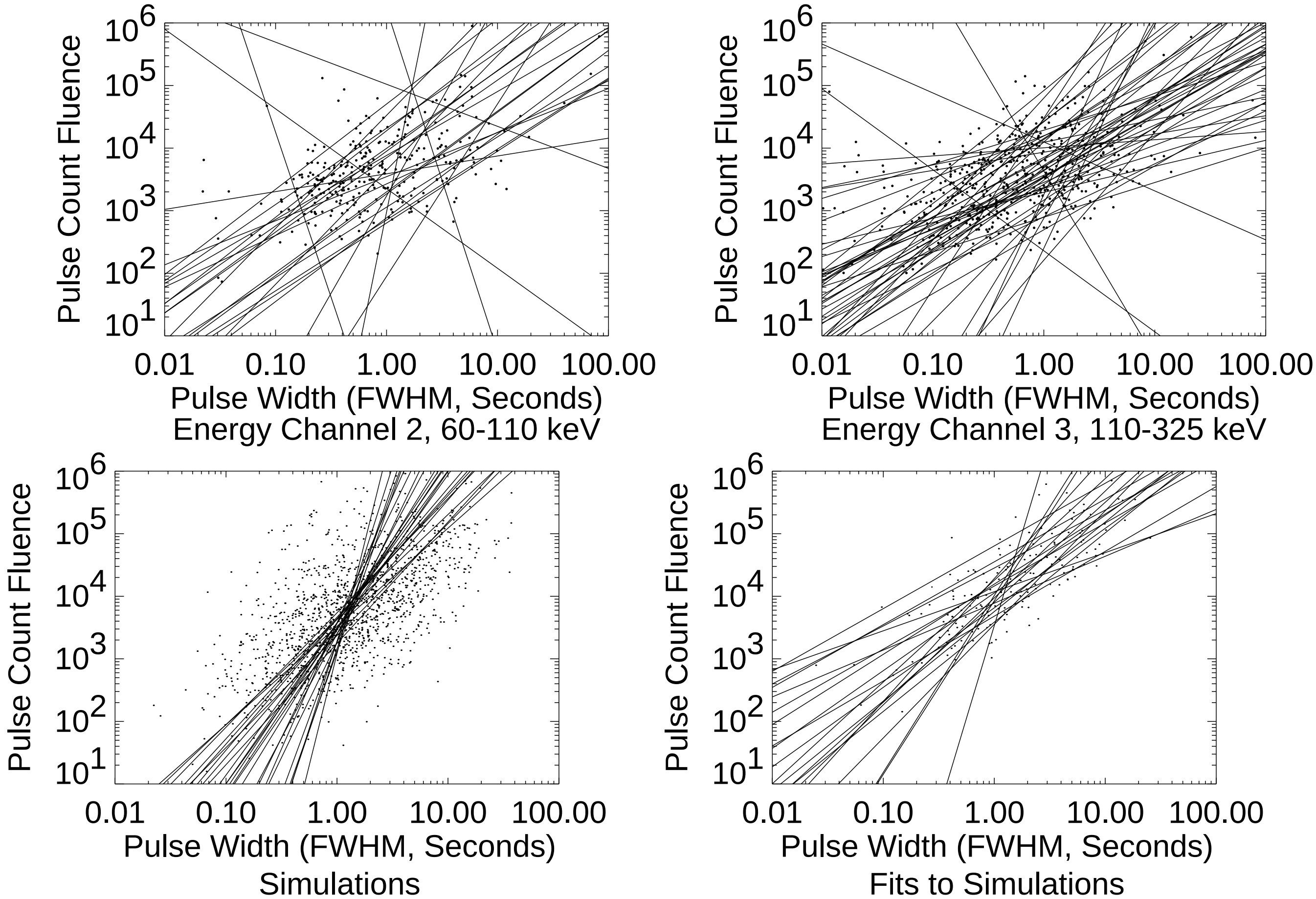

Fig. 11.— Pulse count fluences versus pulse widths within bursts for bursts with strongest correlations. The lines show the fitted power law indices to pulses in individual bursts with strong correlations. In the BATSE bursts (upper panels), nearly all bursts show positive correlations (or slopes), indicating that the distributions of pulse amplitudes within the individual bursts are narrow. In the simulated bursts (lower panels), all bursts show positive correlations between pulse amplitude and pulse width because of the design of the simulation.

Table 7. Correlations Between Pulse Count Fluence and Pulse Width Within Bursts, and Distributions and Medians of the Fitted Power Law Index β.

Energy Channel	% Pos. Corr.	Binom. Prob.	$\beta < -1$	$-1 < \beta < 0$	$0 < \beta < 1$	$\beta > 1$	$\frac{1}{\mathrm{Med.}(1/\beta)}$
1	$66/94 = 70\%$	8.9×10^{-5}	14	15	23	42	1.88
2	$77.5/109 = 71\%$	1.0×10^{-5}	20	13	25	51	1.46
3	$90.5/116 = 78\%$	$< 10^{-16}$	16	12	38	50	1.29
4	$27/35 = 77\%$	0.0013	3	5	17	10	1.03
Sim.	$198/223 = 89\%$	$< 10^{-16}$	14	7	37	165	1.59
Fit to Sim.	$167/198 = 84\%$	$< 10^{-16}$	25	12	54	103	1.41

Table 8. Correlations Between Pulse Count Fluence and Intervals Between Pulses Within Bursts, and Distributions and Medians of the Fitted Power Law Index β.

Energy Channel	% Pos. Corr.	Binom. Prob.	$\beta < -1$	$-1 < \beta < 0$	$0 < \beta < 1$	$\beta > 1$	$\frac{1}{\mathrm{Med.}(1/\beta)}$
1	$33/62 = 53\%$	0.61	21	8.5	14.5	18	13.5
2	$49.5/89 = 56\%$	0.29	19	18	18	34	6.5
3	$54.5/95 = 57\%$	0.15	17	20	24	34	3.1
4	$12/24 = 50\%$	1.0	4	9	7	4	-4.6
Sim.	$71.5/156 = 46\%$	0.30	57	13	18	68	4.1
Fit to Sim.	$63/132 = 48\%$	0.60	45	18	17	52	34

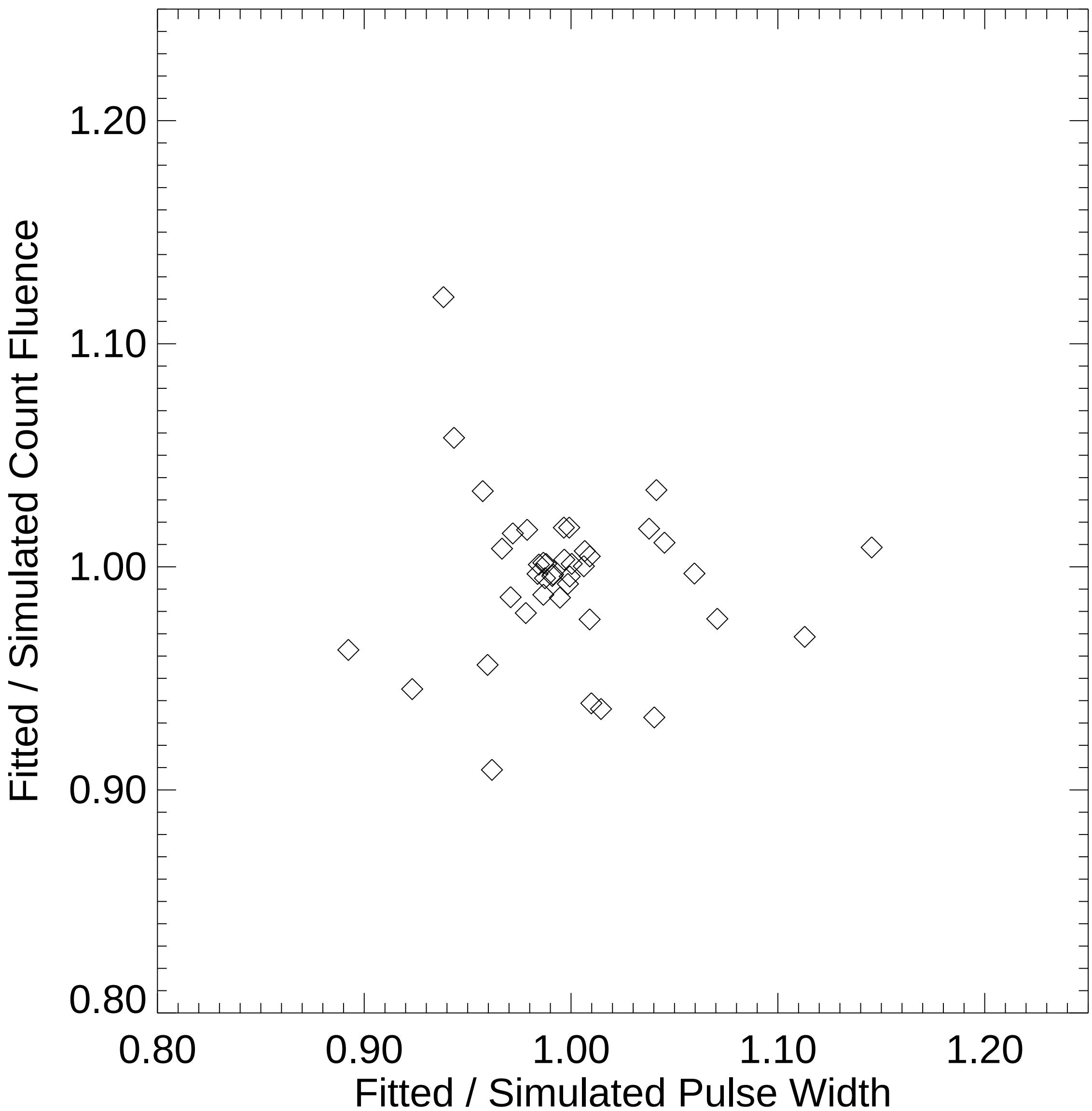

Fig. 12.— Ratios of fitted to simulated pulse count fluences versus ratios of fitted to simulated pulse widths for single-pulse simulated bursts. Note that unlike Figure 8, the errors here do not show any significant correlation.

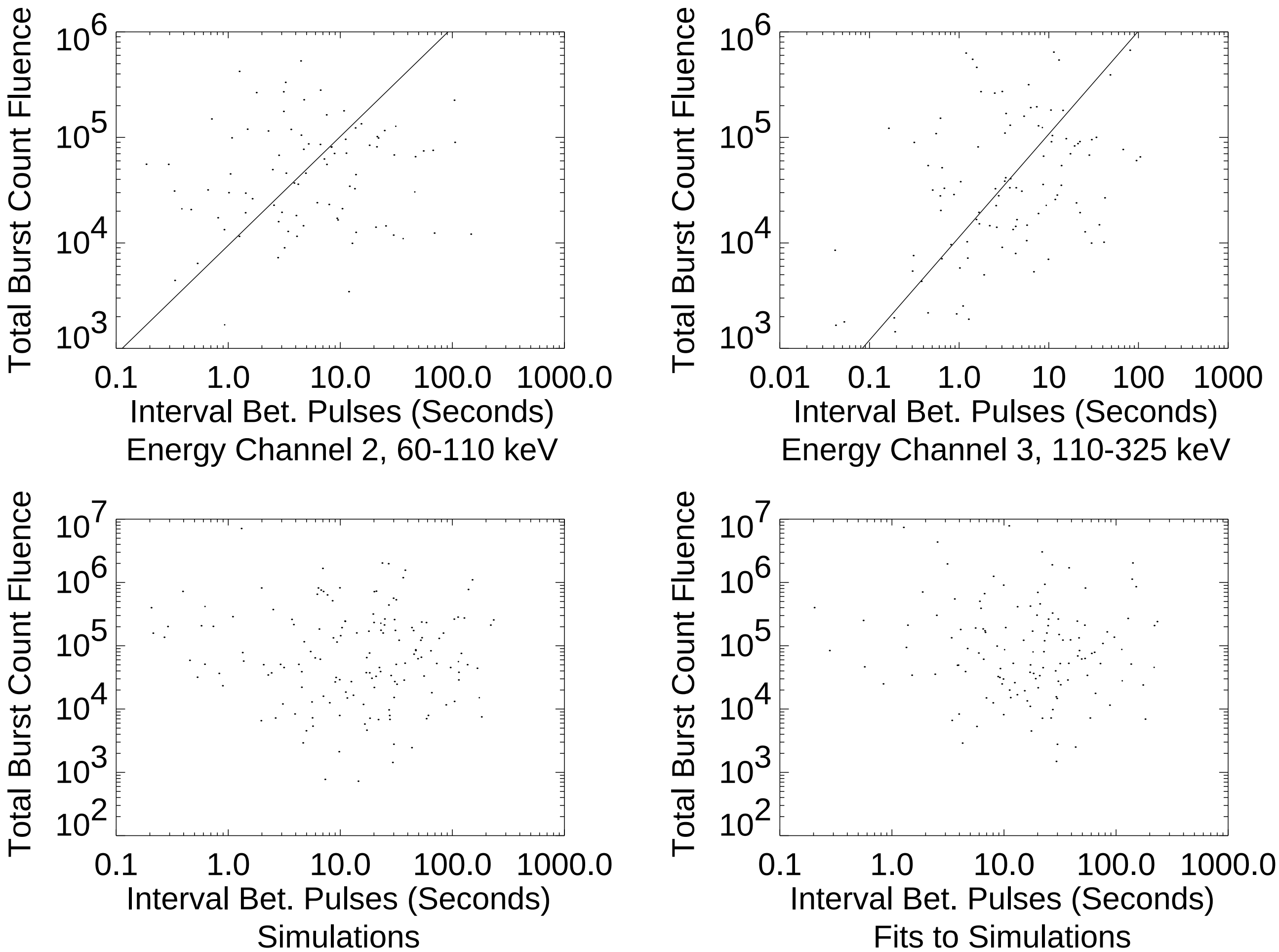

Fig. 13.— Total count fluence versus interval between two highest pulses in each burst. In the initial simulations and the fits to the simulations (bottom panels), the correlations were insignificant, so no fits were made.

The correlation between total *burst* count fluence and the width of the highest amplitude pulse in each burst is probably a result of this correlation and the fact that the majority of the total count fluence of a burst is often contained in a single pulse. The cosmological effects have been overwhelmed by other effects.

It is not clear why there appears to be no correlation between total burst count fluence and the interval between the two highest pulses in each burst. One possibility is that most of the observed bursts are sufficiently far away that the count fluence varies very little with luminosity distance. However, this would place many bursts at redshifts of $z > 10$, which seems unlikely given current evidence.

4. Other Correlations

4.1. Correlations Between Flux and Fluence

Since the count fluence of a pulse scales as the product of its amplitude and its width, and a factor involving the peakedness ν, or equivalently, since the amplitude of a pulse scales as its count fluence divided by its width, again with a factor involving ν, various selection effects could cause observed pulse amplitudes and widths to have an inverse correlation or cause observed pulse count fluences and widths to have a positive correlation.

Figure 14 and Table 9 show that there are no strong correlations between the amplitudes of the highest amplitudes pulses and the total count fluences of the BATSE bursts, in any energy channel. This result is somewhat unexpected, because even in the absence of cosmological effects, we would expect both peak flux and total fluence to scale approximately as the inverse square of the luminosity distance to the sources (the effects of the time dilation factor $1 + z$ are much smaller), and hence to have a positive correlation with each other. The results from our simulations are not helpful because the simulated bursts were also generated with a strong positive correlation between pulse amplitude and pulse count fluence. It appears that selection effects in the pulse-fitting procedure tend to weaken these positive correlations, shown in the last two rows of Table 9, when we compare the simulations with the fits to the simulations. The absence of correlation in the actual bursts may indicate that the intrinsic range of the *effective durations*, *i.e.* the total fluences divided by the peak fluxes (Lee & Petrosian 1997), is large enough to smear out distance effects expected in the distribution of fluences and peak fluxes. It also suggests that if one of the two brightness measures is a good indicator of distance, then the other cannot be, probably due to selection effects, or due to cosmological evolution of the sources.

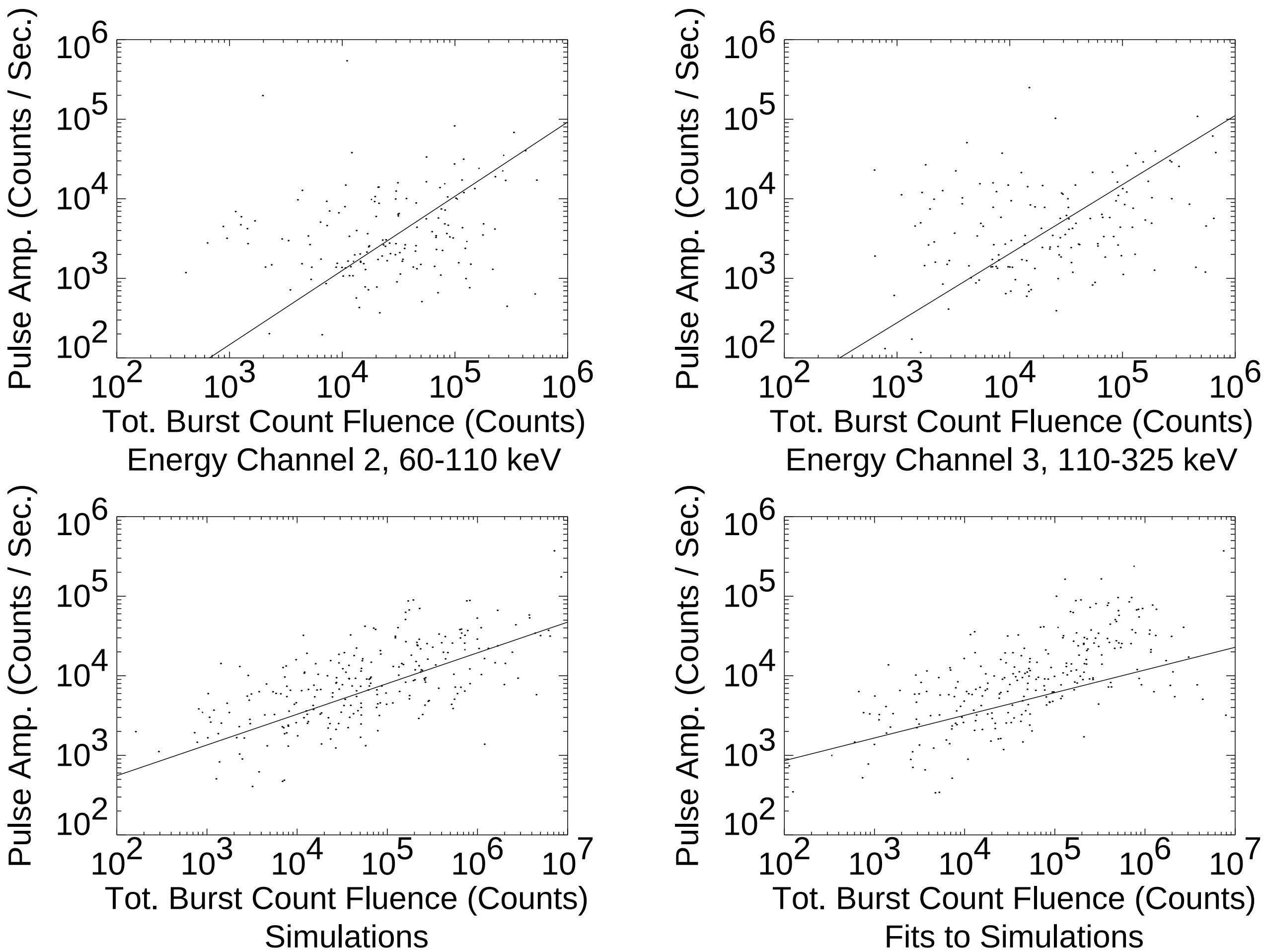

Fig. 14.— Amplitude of highest amplitude pulse versus total count fluence in each burst.

However, when we consider the relation for pulses within individual bursts, we find that a significant majority of bursts in all energy channels show a positive correlation between pulse count fluence and amplitude within bursts. (See Table 10.) In every energy channel, the majority of bursts have pulse amplitudes varying as a small positive power γ of the pulse count fluence within bursts. Most simulated bursts, as expected, show a positive correlation between pulse amplitude and pulse count fluence, but in the fits to the simulations, fewer bursts show a positive correlation. Therefore, the actual correlation in the BATSE bursts may have been weakened by selection effects in the pulse-fitting procedure.

Figure 15 shows an apparent positive correlation between the errors in the fitted pulse amplitudes and fitted count fluences for simulated bursts consisting of a single pulse in both the simulation and the fit. However, the Spearman rank-correlation coefficient shows no significant correlation between the two sets of errors. Therefore, the uncorrelated errors in the pulse amplitudes and pulse count fluences would tend to smear out any existing correlations rather than to create correlations, which is what we have seen above.

4.2. Correlations Between Pulse Amplitude and Pulse Asymmetry

It has been reported that when considering the averaged time profiles of bursts, the decay times from the peaks of bursts show an inverse correlation with peak flux, while the rise times to the peaks of bursts show a smaller inverse correlation or no variation at all with peak flux (Stern et al. 1997b,a; Litvak et al. 1998; Stern et al. 1999). Such a result could not come from cosmological time dilation, but would have to be caused by the burst production mechanism itself, or by some selection effect, perhaps resulting from the BATSE trigger criteria, which selects for fast-rising bursts (Higdon & Lingenfelter 1996), but is independent of burst decay times. It is possible that a similar effect could appear in the individual pulses comprising a burst, as a *positive* correlation between pulse amplitudes and pulse asymmetries as measured by the rise time to decay time ratios. Although there may be selection effects in the pulse-fitting procedure, most of these should affect both rise and decay times similarly, and therefore shouldn't affect pulse asymmetry ratios.

For bursts consisting of a single pulse, the pulse rise and decay times are of course the rise and decay times for the entire burst. Figure 16 shows pulse asymmetries versus pulse amplitudes for these bursts. There does not seem to be any clear correlations in the actual BATSE bursts, but the range of pulse asymmetry ratios appear to be broader for lower amplitude bursts than for higher amplitude bursts. The latter effect could result from the lower signal-to-noise of lower amplitude pulses. The Spearman rank-order correlation coefficients shown in Table 11, columns (a), comparing pulse amplitudes and pulse asymmetries of single-pulse bursts essentially confirm this impression; the correlations for the actual BATSE bursts are very weak, and have different signs in the different energy channels. In the simulated bursts, there are clearly no correlations in either the initial simulations or in the fits to the simulations.

Table 9. Correlation Between Amplitude of Highest Amplitude Pulse and Total Count Fluence in Each Burst, and the Fitted Power Law Index γ.

Energy Channel	r_s	Prob.	γ
1	0.13	0.096	0.92 ± 0.07
2	0.043	0.57	0.93 ± 0.05
3	0.15	0.053	0.87 ± 0.04
4	-0.036	0.77	0.96 ± 0.12
Simulation	0.65	4.4×10^{-36}	0.39 ± 0.03
Fit to Sim.	0.61	8.9×10^{-31}	0.28 ± 0.06

Table 10. Correlations Between Pulse Amplitude and Pulse Count Fluence Within Bursts, and the Distributions and Medians of the Fitted Power Law Index γ.

Energy Channel	% Pos. Corr.	Binom. Prob.	$\gamma < -1$	$-1 < \gamma < 0$	$0 < \gamma < 1$	$\gamma > 1$	Med. γ
1	$71/94 = 76\%$	7.2×10^{-7}	8	18	54	14	0.48
2	$86.5/109 = 79\%$	$< 10^{-16}$	3	23	62	21	0.61
3	$85/116 = 73\%$	4.8×10^{-7}	6	22	75	13	0.63
4	$24/35 = 69\%$	0.028	3	8	19	5	0.61
Sim.	$185/223 = 83\%$	$< 10^{-16}$	11	24	172	16	0.34
Fit to Sim.	$142.5/198 = 72\%$	$< 10^{-16}$	15	40	121	18	0.20

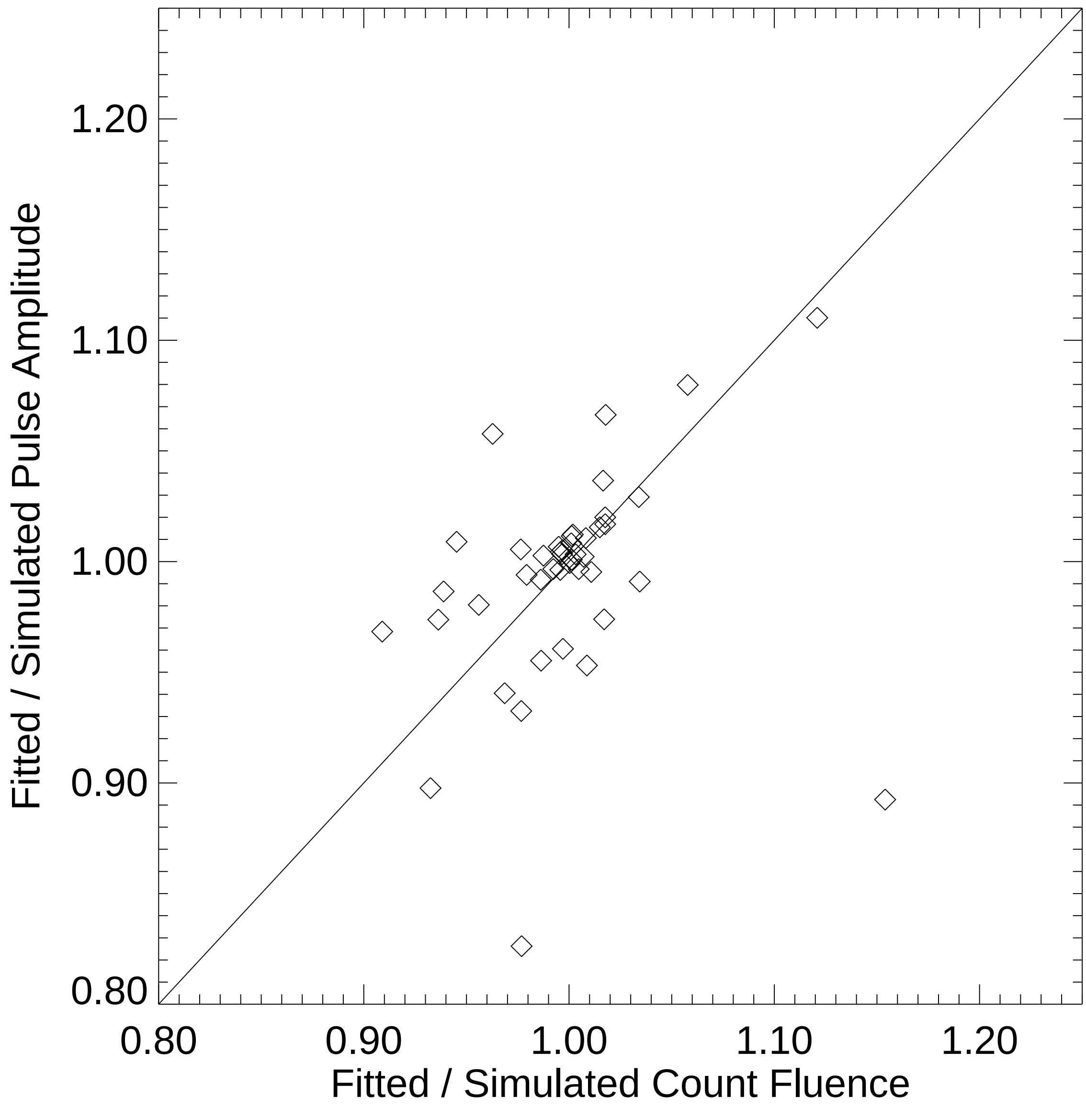

Fig. 15.— Ratios of fitted to simulated pulse amplitudes versus ratios of fitted to simulated pulse count fluences, with line of constant pulse width, for single-pulse simulated bursts. There appears to be a positive correlations between the errors in the fitted pulse amplitudes and count fluences, but the Spearman rank-correlation coefficient shows that they are actually uncorrelated.

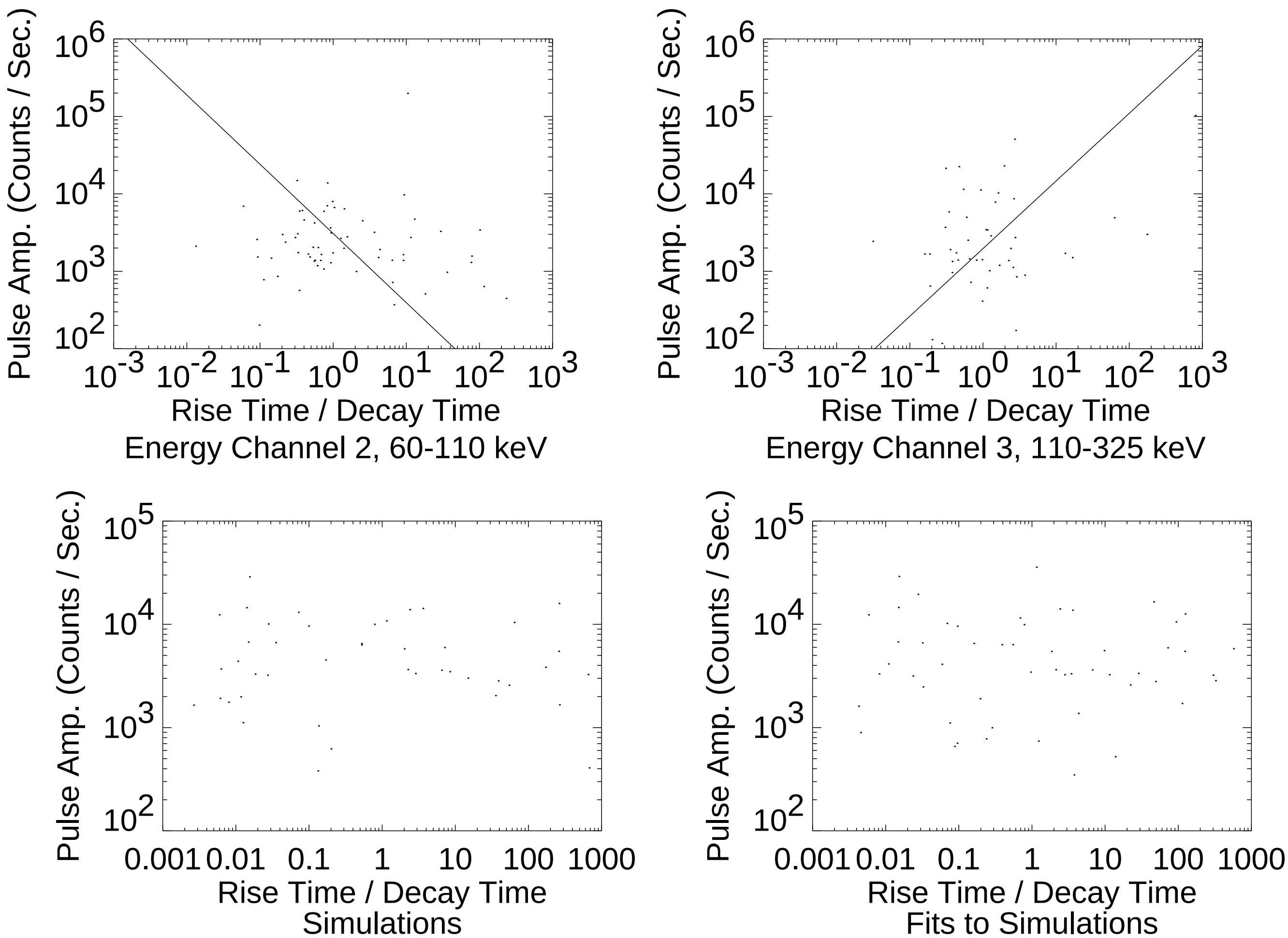

Fig. 16.— Pulse amplitude versus pulse asymmetry for single-pulse fits. In the initial simulations and the fits to the simulations (bottom panels), the correlations were insignificant, so no fits were made.

Although the properties of individual pulses in multiple-pulse bursts may be different from those of the entire bursts, it may still be useful to look for correlations between pulse amplitude and asymmetry for individual pulses in multiple-pulse bursts. For the highest amplitude pulses from each burst, plots of pulse asymmetry versus pulse amplitude are shown in Figure 17, which again show that pulse asymmetries span a larger range of values at lower amplitudes in the actual BATSE bursts. The Spearman rank-order correlation coefficients given in Table 11, columns (b), show a marginally significant inverse correlations in energy channels 1 and 3, a strong inverse correlation in channel 2, and no correlation in channel 4. Again, the simulated bursts show no correlation at all.

Finally, we consider correlations between the amplitudes and asymmetries of pulses within bursts. Table 12 shows characteristics of the distributions of the power law indices δ obtained from fits to these quantities. There do not appear to be statistically significant correlations, except possibly in channel 3.

In summary, there is no clear evidence of any correlations between pulse amplitudes and pulse asymmetry, so that the variations of pulse rise and decay time with pulse amplitude don't appear to be significantly different.

5. Summary and Discussion

In this paper, we use a pulse-fitting procedure to the TTS data from BATSE and determine the amplitudes, rise and decay times, and fluences. We investigate the correlations between all of these parameters of pulses in individual bursts and among different bursts. The former gives a measure of correlations intrinsic to the energy and radiation generation in burst sources, while the latter are also affected by cosmological effects. Simulations are used to determine the biases of the pulse-fitting procedure.

If the peak luminosities of pulses or bursts are approximate standard candles, so that the peak fluxes would be good measures of distance, then we expect to find negative correlations between fluxes and timescales. We do find inverse correlations between the highest pulse amplitude within a burst and two different timescales, the width of the highest amplitude pulse and the time interval between the two highest amplitude pulses. The former correlation, between pulse amplitude and pulse width, which is expected from cosmological time dilation effects, is nevertheless not consistent with purely cosmological effects, but must be at least partially influenced by non-cosmological effects. These non-cosmological effects may include intrinsic properties of the burst sources, or selection effects due to the BATSE triggering procedure, but do not appear to be affected by the pulse-fitting procedure. Our study indicates that the latter correlation, between pulse amplitude and time intervals between pulses, may be less influenced by non-cosmological effects. The inverse correlation observed between pulse amplitude and pulse width within bursts results in part from selection effects in the pulse-fitting procedure, but also appears to result in part from intrinsic

Table 11. Correlation Between Pulse Amplitude and Asymmetry for (a) Single Pulse Bursts and (b) Highest Amplitude Pulse in Each Burst, and the Fitted Power Law Index δ.

Energy	(a) Single Pulse Bursts			(b) Highest, All Bursts		
Channel	r_s	Prob.	δ	r_s	Prob.	δ
1	-0.25	0.049	-0.91 ± 0.10	-0.24	0.0020	-0.89 ± 0.06
2	-0.27	0.022	-0.89 ± 0.20	-0.32	1.7×10^{-5}	-0.84 ± 0.06
3	0.01	0.93	0.87 ± 0.11	-0.15	0.051	-0.99 ± 0.04
4	-0.27	0.12	-0.86 ± 0.20	-0.13	0.30	-0.26 ± 0.09
Sim.	0.11	0.42	$\cdots$	0.081	0.17	$\cdots$
Fit to Sim.	-0.0059	0.96	$\cdots$	0.066	0.27	$\cdots$

Table 12. Correlations Between Pulse Asymmetry and Amplitude Within Bursts, and the Distributions and Medians of the Fitted Power Law Index δ.

Energy Channel	% Pos. Corr.	Binom. Prob.	$\delta < -1$	$-1 < \delta < 0$	$0 < \delta < 1$	$\delta > 1$	Med. δ
1	$47/94 = 50\%$	1	7	42	36	9	-0.029
2	$60/109 = 55\%$	0.29	6	48	44	11	-0.066
3	$70.5/116 = 61\%$	0.020	5	52	50	9	0.077
4	$17/35 = 49\%$	0.87	2	16	14	3	-0.090
Sim.	$109/223 = 49\%$	0.74	5	106	103	9	0.0068
Fit to Sim.	$100/198 = 51\%$	0.89	13	81	94	10	0.063

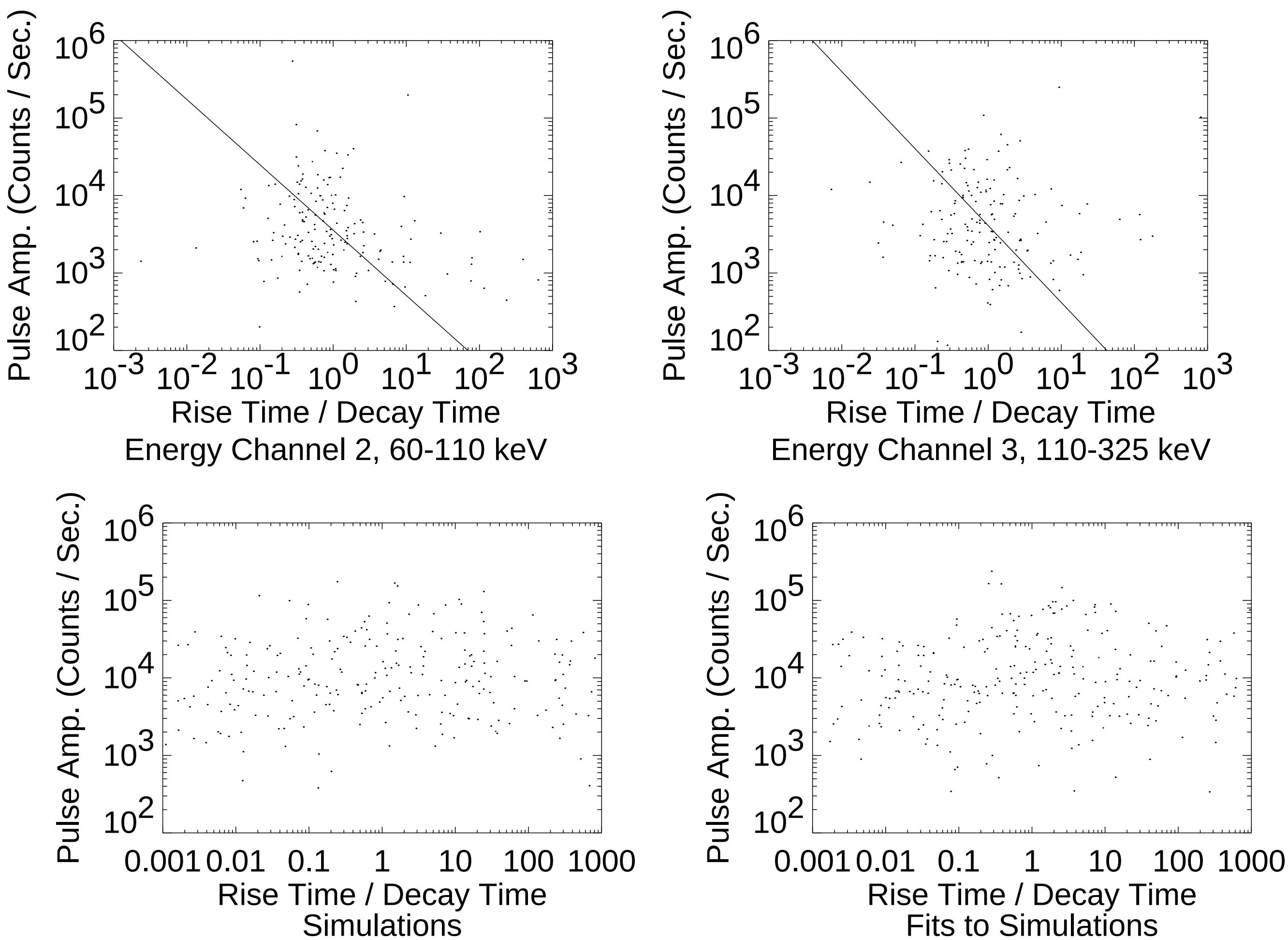

Fig. 17.— Pulse amplitude versus pulse asymmetry for highest amplitude pulse in each burst. In the initial simulations and the fits to the simulations (bottom panels), the correlations were insignificant, so no fits were made.

properties of the burst sources.

If the total radiated energies of bursts are approximate standard candles, so that the burst fluences would be good measures of distance, then we expect to find negative correlations between fluences and timescales. We find instead a *positive* correlation between the total burst count fluence and the width of the highest amplitude pulse, but no correlation with the time interval between the two highest amplitude pulses. The former correlation indicates that non-cosmological effects are stronger than any cosmological effects. This is supported by the positive correlation between pulse amplitude and pulse count fluence within bursts. However, it is not clear why total burst count fluence and time intervals between pulses show no correlation.

It is natural to expect that the peak flux of bursts and the total count fluence of bursts should both decrease essentially the same way (except for a factor of $1+z$) as the distance to the burst sources increase. This would suggest that there should be positive correlations between the peak flux of bursts and the total count fluence of bursts. Strangely, the highest pulse amplitude and the total count fluence of bursts appear to have no statistically significant correlation with each other, implying that the two measures of brightness cannot both be good standard candles; at least one, or more probably both, are poor measures of distance.

There do not appear to be any statistically significant correlations between pulse amplitude and pulse asymmetry, whether the comparison is i) of all pulses in all bursts combined, ii) of only the highest pulse in each burst, iii) of only the single-pulse bursts, or iv) of different pulses within multiple-pulse bursts. This implies that the differences between the variations of pulse rise and decay time with pulse amplitude are statistically insignificant, and both rise times and decay times tend to decrease as pulse amplitude increases.

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