Properties of Short Gamma-ray Burst Pulses from a BATSE TTE GRB Pulse Catalog

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Abstract

We analyze pulse properties of short gamma-ray bursts (GRBs) from a new catalog containing 434 pulses from 387 BATSE time-tagged event (TTE) GRBs. Short GRB pulses exhibit correlated properties of duration, fluence, hardness, and amplitude, and they evolve hard to soft while undergoing similar triple-peaked light curves similar to those found in long/intermediate bursts. We classify pulse light curves using their temporal complexities, demonstrating that short GRB pulses exhibit a range of complexities from smooth to highly variable. Most of the bright, hard, chaotic emission seen in complex pulses seems to represent a separate highly variable emission component. Unlike long/intermediate bursts, as many as 90% of short GRBs are single-pulsed. However, emission in short multipulsed bursts is coupled such that the first pulse’s duration is a predictor of both the interpulse separation and subsequent pulse durations. These results strongly support the idea that external shocks produce the prompt emission seen in short GRBs. The similarities between the triple-peaked structures and spectral evolution of long, short, and intermediate GRBs then suggests that external shocks are responsible for the prompt emission observed in all GRB classes. In addition to these findings, we identify a new type of gamma-ray transient in which peak amplitudes occur at the end of the burst rather than at earlier times. Some of these “crescendo” bursts are preceded by rapid-fire “staccato” pulses, whereas the remaining are preceded by a variable episode that could be unresolved staccato pulses.

Key words: astronomical databases: miscellaneous – gamma-ray burst: general – methods: data analysis – methods: statistical

Supporting material: figure sets, machine-readable tables

1. Introduction

Gamma-ray bursts (GRBs) radiate at such large rates over tens of milliseconds to hundreds of seconds that they must by necessity extract their energies ($E_{\text{tot}} \approx 10^{51}$ erg; Frail et al. 2001; Panaitescu & Kumar 2001; Piran et al. 2001) from the violent gravitational collapse that accompanies black hole formation. Production of these energy rates could require a variety of progenitors: in the 1990s the broad logarithmic distribution of GRB durations (spanning six decades) showed evidence of bimodality, with long and short bursts separated at roughly $T_{90} \approx 2$ s (Kouveliotou et al. 1993). Bursts in the long class were shown to have softer average spectral hardnesses than those in the short class. Theoretical models favoring accretion scenarios involving stellar cores have difficulty explaining GRB timescales shorter than 2–3 s (e.g., Woosley 1993), supporting the idea of a second GRB population arising from merging neutron stars or other compact massive objects.

Significant evidence has been presented indicating that long and short GRB classes represent different source populations (Norris et al. 2001; Baláz et al. 2003; Piran 2004; Zhang et al. 2009; Lu & Liang 2010; Li et al. 2016). These two burst classes appear to originate in different types of host galaxies, belong to different redshift distributions, and produce different types of afterglows (e.g., Hogg & Fruchter 1999; Hjorth et al. 2006; Berger 2014). Some low-luminosity long GRBs have been associated with Type Ic supernovae (SNe; Hjorth et al. 2003; Campana et al. 2006; Pian et al. 2006; Blanchard et al. 2016), supporting the idea that the long GRBs in general are related to deaths of massive stars (Woosley 1993; Paczynski 1998; Woosley & Bloom 2006; Blanchard et al. 2016). In contrast, short GRBs are found in metal-poor regions and are less luminous than long GRBs, suggesting origins from compact binary mergers (Paczynski 1986; Usov 1992; Berger 2014).

Despite this supportive evidence, the apparent clarity of the simple $T_{90}$-based classification scheme used by many is a stark oversimplification. Application of statistical clustering techniques and machine learning algorithms to prompt emission properties indicate that GRBs fall into three or more separate classes (Horváth 1998; Mukherjee et al. 1998; Hakkila et al. 2000; Balastegui et al. 2001; Horváth 2002; Rajaniemi & Mähönen 2002; Hakkila et al. 2003; Borgonovo 2004; Horváth et al. 2006; Chattopadhyay et al. 2007; de Ugarte Postigo et al. 2011; Zitouni et al. 2015; Zhang et al. 2016; Chattopadhyay & Maitra 2017). The favored solution involves long, short, and intermediate classes identified on the basis of duration, hardness, and fluence. This result has been repeatedly found from observations by many GRB experiments, including BATSE (the Burst And Transient Source Experiment on NASA’s Compton Gamma Ray Observatory), BeppoSAX, Swift, and Fermi GBM (e.g., Horváth et al. 2008; Horváth 2009; Huja et al. 2009; Horváth et al. 2010; Horváth & Tóth 2016). The intermediate GRB class is composed of bursts with durations overlapping short and long bursts and is characterized by GRBs having the softest spectra. However, only weak evidence has been provided arguing that the intermediate class might be a distinctly different source population (the angular distribution of intermediate GRBs is anisotropic at around the 2σ significance level), and theoretical models have been unable to account for them. Few studies have tried to explain the
existence of the intermediate class, although Hakkila et al. (2003) proposed that this class could result from instrumental biases: intermediate GRBs are faint, soft, long-duration bursts that appear to be a separate class because they are found close to the trigger threshold.

With little evidence that the intermediate class makes up a separate source population, one is forced to reassign each intermediate GRB to either the long or the short class. The long/short GRB duration boundary is therefore even less clear than implied by the simple $T_{90} \approx 2$ s dividing line, and additional parameters such as spectral hardness and fluence are likely needed before assigning bursts near this line to a class. This is problematic, as short and long GRB class characteristics depend on the instrument that observes them, the classification techniques used, and the specific set of bursts being classified. In other words, each gamma-ray instrument has its own spectral and intensity response, which can lead to redefinitions of the burst class properties and their associated dividing lines. Modern statistical and machine learning classification techniques are powerful tools that are sensitive to the aforementioned data characteristics, if the instrumental characteristics are also accounted for. In the reassignment of intermediate BATSE bursts, we have found that short hard GRBs generally belong to the short class, while short soft GRBs generally belong to the long class.

Pulses, the basic units of GRB prompt emission, have the potential of delineating long and intermediate GRBs from short GRBs. Pulses are pervasive and have well-defined light curves as opposed to representing stochastic or chaotic emission. Isolated pulses observed by BATSE, Swift, and Fermi exhibit hard-to-soft evolution, longer durations at lower energies, near-simultaneous initiation across the range of observed energies, asymmetric shapes, and triple-peak structures with rehardening occurring around the time of each peak. Most of these pulse behaviors have been found in long, short, and intermediate bursts, but the triple-peak pulse structure has not been systematically studied in short bursts. In BATSE archival data, this is because most observations are limited to data having 64 ms resolution, which is often longer than the durations of the expected triple-peak substructures. In Swift data, it is because Swift’s spectral response favors detection of soft GRBs over hard ones, making the division between long and short GRBs less clear. An analysis of BATSE short bursts can be performed using the instrument’s time-tagged event (TTE) data type and is described in this paper. An extensive high time resolution study of short Fermi GRBs is also possible and will be examined in a separate paper.

BATSE (e.g., Horack 1991; Fishman 2013) was composed of eight large sodium iodide detectors located on the outside of the Compton Gamma-Ray Observatory; the faces of these detectors were arranged to describe the shape of a regular octahedron. Gamma- and X-ray photons absorbed by the sodium iodide detectors produced visible photons of roughly proportional energy that were detected by photomultipliers; these counts were parsed into four energy channels (channel 1: energies of 20–50 keV; channel 2: energies of 50–100 keV; channel 3: energies of 100–300 keV; channel 4: energies of 300 keV–1 MeV). Photon counts were collected in the form of a changing instrumental background throughout the mission on 1 s timescales; the format of this data stream changed at the moment an onboard trigger occurred, at which time the instrument switched to 64 ms resolution data for the duration of an event. A trigger occurred when the counts rose above a specified statistical threshold (usually 5.5σ) of the signal (measured on three different trigger timescales: 64, 256, and 1024 ms) relative to the background (based on a 17 s running average count rate) in a predefined set of energy channels (generally channels 2 and 3 spanning the 50–300 keV energy range) in each of the two BATSE detectors most nearly facing the source (to eliminate single-detector particle events).

In addition to the data having 64 ms resolution, BATSE also collected a limited amount of high time resolution data referred to as TTE data. TTE data, containing specific information on each photon collected, were stored in a ring buffer starting around the time of the instrumental trigger. Photons were included in the buffer until it was filled, which generally spanned a time interval of no more than 2 s. If the count rate was too high, the buffer contained fewer than 2 s worth of photon counts. The energy of each photon was independently measured and stored in the buffer.

Because of BATSE’s large surface area and energy response, BATSE TTE data have sufficient temporal resolution and counts to permit useful and unique analyses of some short and intermediate GRB light curves. Short and intermediate GRB light curves can be fully contained within the TTE ring buffer, whereas long bursts cannot. The high time resolution of TTE data allows for the the study of temporal structures within these bursts that cannot be performed with the lower-resolution 64 ms data. Additionally, count rates are often high enough for detected photons to be parsed into different energy bins, and the four-channel properties of the 64 ms data can be reproduced on shorter timescales.

BATSE TTE data allow several important yet unanswered questions about GRB pulse structure to be addressed: Do short GRB pulse light curves contain the same triple-peak, hard-to-soft evolutionary structures exhibited by long and intermediate GRB pulses? Do short GRB pulse spectra reharden at the time of each of the three pulse peaks as they do for long and intermediate GRB pulses? How do the spectrotemporal characteristics of short GRB pulses contrast with those of long and intermediate pulses? Can pulse characteristics be used to differentiate between short and intermediate or long GRB pulses? To answer these questions, we have undertaken a systematic study of short-duration BATSE GRBs using TTE data.

2. TTE Pulse Fitting

BATSE obtained TTE data for 532 GRBs (2702 GRBs appear in the online BATSE Burst Catalog; M. S. Briggs et al. 2018, in preparation, at https://gammaray.msfc.nasa.gov/batse/grb/catalog/current/). Some of these are long GRBs with durations extending far beyond the 2 s maximum boundary of the TTE window, leaving a smaller number of shorter bursts available for high-resolution pulse analysis. Our initial sample consists of 392 of these BATSE TTE GRBs obtained from Horváth et al. (2005); these GRBs are all short enough to potentially fit completely within their respective TTE windows. The photon counts of these bursts have been subdivided into 4 ms bins, as well as into the four standard BATSE energy channels.

The values we are fitting are the 4 ms binned counts summed over the four BATSE energy channels. These are short-duration
GRBs having spectrottemporal resolutions similar to those of the 64 ms long and intermediate BATSE and Swift bursts used in prior pulse analyses (Hakkila & Preece 2014; Hakkila et al. 2015). Upon removal of five bursts with data problems, the sample available for GRB pulse fitting is reduced to 387 bursts.

2.1. The Pulse-fitting Model

The pulse-fitting model consists of two parts. The first is the general four-parameter empirical pulse model of Norris et al. (2005). The hypothesis is that a GRB emission episode can be modeled by the following asymmetric, monotonically increasing and decreasing intensity function:

\[ I(t) = A \lambda e^{-\gamma(t-t_s)-\tau(t-t_s)/\tau_2}, \]

where \( t \) is time since trigger, \( A \) is the pulse amplitude, \( t_s \) is the pulse start time, \( \tau_1 \) is the pulse rise parameter, \( \tau_2 \) is the pulse decay parameter, and the normalization constant \( \lambda \) is given as \( \lambda = \exp[2(\tau_1/\tau_2)^{1/2}] \). Poisson statistics and a two-parameter background counts model of the form \( B = B_0 + BS \times t \) are assumed (where \( B \) is the background counts in each bin and \( B_0 \) and \( BS \) are constants denoting the mean background (counts) and the rate of change of this mean background [counts s\(^{-1}\)]. Observable pulse parameters obtained from this model include the pulse peak time \( \tau_{\text{peak}} \) where

\[ \tau_{\text{peak}} = t_s + \sqrt{\tau_1/\tau_2}, \]

along with the pulse duration \( w \) and the pulse asymmetry \( \kappa \). As a result of the rapid smooth rise and fall of the pulse model, \( w \) and \( \kappa \) are measured relative to some fraction of the peak intensity. Using the fraction previously described (Hakkila & Preece 2011) as \( I_{\text{meas}}/I_{\text{peak}} = e^{-\mu} \) (corresponding to 4.98% \( I_{\text{peak}} \)),

\[ w = \tau_2[9 + 12\mu]^{1/2}, \]

where \( \mu = \sqrt{\tau_1/\tau_2} \), and

\[ \kappa \equiv [1 + 4\mu/3]^{-1/2}. \]

Asymmetries range from symmetric (characterized by \( \kappa = 0 \)) to asymmetric having longer decay times than rise times \( (0 < \kappa \leq 1) \). The Norris et al. (2005) pulse model cannot physically describe pulses in which asymmetries are characterized by longer rise than decay times, but it provides a good first-order fit to BATSE, Fermi GBM, and Swift pulses.

Residuals to the Norris et al. (2005) model can be produced by subtracting each best-fit model from an observed pulse light curve. Small yet distinct deviations in the residuals are found to be systematically in phase with the light curve (Hakkila & Preece 2014), and these deviations are needed to accurately describe GRB pulse shapes. Although the deviations are closely aligned with the pulse duration, they are not always contained within it. Thus, we have defined the larger fiducial time interval \( W_{\text{fid}} \) as

\[ W_{\text{fid}} = \tau_{\text{end}} - \tau_{\text{start}} = 4.4\tau_2(\sqrt{1+\mu/2} + 1) + \sqrt{\tau_1/\tau_2}, \]

with the fiducial end time \( \tau_{\text{end}} \) given by

\[ \tau_{\text{end}} = \frac{w}{2}(1 + \kappa) + t_s + \tau_{\text{peak}} \]

and the fiducial start time \( \tau_{\text{start}} \) given by

\[ \tau_{\text{start}} = t_s - 0.1 \left[ \frac{w}{2}(1 + \kappa) - \tau_{\text{peak}} \right]. \]

The strange, wavelike pattern of the residual variations can be fitted with an empirical function (Hakkila & Preece 2014):

\[
\text{res}(t) = \begin{cases} 
  a_0(\sqrt{\Omega(t_0 - t - 0.005)}) & \text{if } t < t_0 - 0.005 \\
  a_0(\sqrt{\Omega(t_0 - t - 0.005)}) & \text{if } t_0 - 0.005 < t \leq t_0 + 0.005 \\
  a_0(\sqrt{\Omega(t - t_0 - 0.005)}) & \text{if } t > t_0 + 0.005.
\end{cases}
\]

Here \( a_0(x) \) is an integer Bessel function of the first kind, \( t_0 \) is the time of the residual peak (measured from the trigger time), \( a \) is the amplitude of the residual peak, \( \Omega \) is the Bessel function’s angular frequency that defines the timescales of the residual wave (a large \( \Omega \) corresponds to a rapid rise and fall), and \( s \) is a scaling factor that relates the fraction of time that the function before \( t_0 \) has been compressed relative to its time-inverted form after \( t_0 \). The time during which the pulse intensity is a maximum is required to be a plateau instead of a peak, with a duration of \( \omega_{\text{plateau}} \approx 0.01\omega_{\text{fid}} \). Since there is no evidence in the pulse shape that the Bessel function continues beyond the third zero (following the second half-wave), the function is truncated at the third zeros \( J_0(\pi x) \approx 0.005 x = 8.654 \).

The fiducial values can be converted back to values in the measured time interval using

\[ a_{\text{meas}} = a, \]

\[ s_{\text{meas}} = s, \]

\[ t_{0,\text{meas}} = t_0(t_{\text{end}} - t_{\text{start}}) + t_{\text{start}} \]

and

\[ \Omega_{\text{meas}} = \Omega/(t_{\text{end}} - t_{\text{start}}), \]

where \( t_{\text{start}} \) and \( t_{\text{end}} \) are the real time values corresponding to the start and end of the fiducial duration.

A convenient way to describe the pulse residual amplitudes is to normalize them to the pulse fit amplitudes, producing an intensity quantity that is independent of the instrument’s signal-to-noise ratio (S/N). The relative amplitude \( R \) is given by

\[ R = a/A. \]

The 4 ms S/N is a measure of the peak brightness of each TTE GRB, relative to its background count measured with 4 ms temporal resolution. The S/N is

\[ S/N = (P_4 - B)/\sqrt{P_4}, \]

where \( P_4 \) is the 4 ms peak count and \( B \) is the mean background count. This S/N is primarily appropriate when analyzing GRB pulses fit on the 4 ms timescale.

2.2. TTE Pulse-fitting Methodology

The technique we use for extracting pulses from TTE light curves is a modification of that described previously (e.g., Hakkila & Preece 2014 and references therein). This is because we have changed our expectations about the monotonic nature of GRB pulses based on our previous analyses. The 4 ms TTE light curves we are using generally exhibit clearly defined,
isolated emission episodes, and many of these episodes appear to have shapes that are consistent with those identified for long/intermediate GRB pulses. Our a priori expectation of multiple peaks, rather than of strict monotonicity, allows us to hypothesize that every emission episode contains a potential pulse, with light curves that might be improved with the addition of the Hakkila & Preece (2014) residual function. Overlapping pulses will be problematic, but these would have been problematic even if we had assumed that every bump in the light curve represented a monotonic, overlapping pulse. However, we can check our results for short GRB pulses against our prior results for long/intermediate GRB pulses as our analysis proceeds.

This GRB pulse analysis approach is more comprehensive and systematic than any of our previous studies involving BATSE, Swift, and Fermi GBM 64 ms data. Here we attempt to analyze all bursts that entirely or mostly fit in the TTE temporal window, in contrast to the prior selection criterion of only bursts that appear to be composed of single, isolated pulses (from the 64 ms studies). This TTE study thus depends primarily on the duration of the fitted pulse, and not on how easy it is to fit the light curve. This allows us to estimate completeness for our results.

3. The BATSE TTE Pulse Catalog

The final BATSE TTE pulse catalog consists of 434 pulses found in 387 GRBs. Of the 387 TTE bursts for which TTE data are available, 206 completely fit within the TTE temporal window and 181 partially fit within the TTE temporal window. GRBs that completely fit within the window have been analyzed using 4 ms resolution data (TTE complete pulses), while those that do not have been analyzed using 64 ms resolution (TTE partial pulses).

The BATSE trigger is responsible for the fact that some short bursts do not completely fit within the TTE temporal window. For BATSE to trigger, at least two of the LADs (Large Area Detectors) need to accumulate a necessary number of photon counts (typically 5.5σ above the background) in a predefined set of energy channels (generally channels 2 and 3 spanning 50–300 keV) on one of three trigger timescales (64, 256, and 1024 ms). Because GRB light curves have different peak intensities, spectral hardnesses, and variability, the times at which TTE windows start can be misaligned with the trigger times. The TTE window is so short that some of the TTE accumulation can occur prior to the trigger; when this happens, the light curve found in the TTE window is incomplete.
Additionally, the TTE window is not really a temporal window, but rather one based on photon count accumulation. If a burst is bright, then photon counts can fill the buffer quickly, and the TTE window will be shorter than 2 s. Examples of these effects are demonstrated in Figure 1 for six TTE partial pulses.

Light curves for all fitted GRB pulses and their residuals are available from The Astrophysical Journal in the form of online electronic figures.

3.1. Extended Burst Classification Based on Duration, Hardness, and Fluence

The 2 s temporal limit of the BATSE TTE window suggests that most TTE bursts belong to the short GRB class. Rather than accepting this at face value using the “$T_{90} \leq 2$ s” assertion, we prefer to classify GRBs using a formal statistical clustering or data mining technique. As discussed previously (see Section 1), formal techniques commonly prefer three GRB classes over two. Since the assignment of any GRB to a specific class depends on the classification technique being used, the burst characteristics being assessed, and the data set being analyzed, we must choose a methodology for classifying the bursts in our sample. The three-class model obtained by Horváth et al. (2006), obtained through application of principal component analysis (PCA) to GRB duration, fluence, and hardness data (Bagoly et al. 1998; Balázsz et al. 2003), provides a thoughtful systematic basis for classification. Unfortunately, Horváth et al. (2006) do not provide classifications for many of the BATSE GRBs in our sample.

We can extend the Horváth et al. (2006) results to our TTE data set using rules developed from supervised classification techniques. Our choice of a supervised classification algorithm is the decision tree C4.5 (Quinlan 1993), found in the WEKA freeware suite of data mining tools under the J48 implementation (Frank et al. 2016). We use the classification results of Horváth et al. (2006), combined with the durations, fluences, and spectral hardesses of all bursts found in the BATSE Final Catalog (https://gammaray.msfc.nasa.gov/batse/grb/catalog/current/). J48 uses previously classified bursts (a training set) to identify simple IF THEN ELSE classification branch rules. Each IF THEN ELSE statement is a branch on this classification tree, and the terminal branches are referred to as leaves. A measure of entropy determines whether or not information is gained through the branching process. As it is being developed, a classification tree can be pruned if desired to eliminate sparsely filled leaves. Once a classification tree exists, the IF THEN ELSE rules can be used to classify unknown objects while assigning to each a probability that each has been placed in the appropriate class.

For this application of J48, we use the default parameter settings, which are known to generally provide a good performance (Frank et al. 2016). Pruning has been disabled because our goal is to extend rather than generalize the Horváth et al. (2006) classification scheme. However, in order to avoid having rules that apply to individual bursts, the minimum number of objects per leaf has been set to two.

The resulting J48 tree has 14 leaves developed from 1557 GRBs using the attributes of logarithmic duration, hardness (channel 3/channel 2), and fluence, with a 97.88% accuracy. The confusion matrix demonstrates the effectiveness of the resulting rule set: diagonal matrix elements indicate agreement between J48 and the original classification for 1524 long (L), short (S), and intermediate (I) GRBs, while off-diagonal elements show how the remaining 33 GRBs are misclassified.

|   | L | S | --- |
|---|---|---|-----|
| 125 | 5 | 16 | I   |
| 6  | 1003 | 0 | L   |
| 5  | 1 | 396 | S   |

The final J48 tree shows the rules for each leaf, with parentheses indicating the number of originally and reclassified GRBs placed in the leaf:

$$\text{log}(\text{dur}) < 0.73,$$
$$\text{log}(\text{dur}) < 0.382,$$
$$\text{log}(\text{dur}) < -0.049: \text{S (279.0)},$$
$$\text{log}(\text{dur}) > 0.049,$$
$$\text{log}(\text{hr}) < 0.307: \text{I (15.0}/5.0),$$
$$\text{log}(\text{hr}) > 0.307: \text{S (111.0}/8.0),$$
$$\text{log}(\text{dur}) > 0.382,$$
$$\text{log}(\text{hr}) < 0.689: \text{I (63.0)},$$
$$\text{log}(\text{hr}) > 0.689,$$
$$\text{log}(\text{dur}) < 0.561: \text{S (22.0}/8.0),$$
$$\text{log}(\text{dur}) > 0.561: \text{I (21.0)},$$
$$\text{log}(\text{dur}) > 0.73,$$
$$\text{log}(\text{dur}) < 0.933,$$
$$\text{log}(\text{hr}) < -0.143: \text{I (11.0)},$$
$$\text{log}(\text{hr}) > -0.143,$$
$$\text{log}(\text{hr}) < 0.775,$$
$$\text{log}(\text{hr}) < 0.1,$$
$$\text{log}(\text{S}) < -6.005: \text{I (4.0)},$$
$$\text{log}(\text{S}) > -6.005,$$
$$\text{log}(\text{S}) < -5.75: \text{L (3.0)},$$
$$\text{log}(\text{S}) > -5.75: \text{I (2.0)},$$
$$\text{log}(\text{hr}) > 0.1,$$
$$\text{log}(\text{S}) < -6.31: \text{I (3.0}/1.0),$$
$$\text{log}(\text{S}) > -6.31: \text{L (28.0}/1.0),$$
$$\text{log}(\text{hr}) > 0.775: \text{I (17.0}/5.0),$$
$$\text{log}(\text{dur}) < 0.933: \text{L (978.0}/5.0).$$

The long and short GRB classes are clearly identified at the ends of the duration distribution, as 97% (983/1009) of the long bursts have $T_{90} > 8.57$ s and 68% (279/412) of the short bursts have $T_{90} \leq 0.89$ s. The rules for classifying short GRBs are more successful (97% of the time for 398/412) when spectral hardness is also included (119 additional short GRBs are characterized by $0.89 < T_{90} < 2.41$ s and hr > 2.03). However, both short and intermediate bursts are found in the time interval spanned by the TTE window ($0.89 < T_{90} < 2$ s).

We can assign probable class membership to each previously unclassified GRB using these J48 rules. Some bursts are more difficult to classify because they lack one or more of the classification attributes, so J48 assigns greater uncertainty to these classifications. However, bursts lacking one or more classification attribute are rare, so most of the probabilities that a burst belongs to a preferred class exceed 90%. As a result, we consider burst classification probabilities of less than 90% to represent questionable (denoted with a “?” in our catalog) class assignments.

The classification results, shown in Table 1, verify that most (≈90%) of the TTE GRBs belong to the short GRB class. Use of these classification values allows us to examine the characteristics of short GRB pulses with greater confidence than can be found by defining short GRBs only as those having $T_{90} < 2$ s.
Thirty-two Pulse Classification Based on Complexity

We use an iterative, heuristic approach to GRB pulse classification in order to recognize our partial yet still incomplete understanding of GRB pulse behaviors. This approach allows us to find and account for pulse behaviors that we expect while also allowing us to search for behaviors that we may not anticipate. An approach of this type (part statistical, part data mining) is needed because GRB pulses do not act like pulses in the standard sense of the term.

The Oxford English Dictionary defines a pulse as “a single vibration or short burst of sound, electric current, light, or other wave.” The standard assumption has been that that GRB pulses are monotonic structures over-stochastically varying backgrounds. Although this assumption has been applied almost universally in GRB pulse fitting, the residuals of isolated GRB pulses demonstrate that it is not always valid (Hakkila & Preece 2014; Hakkila et al. 2015). There are negative repercussions to the measurement of GRB pulse properties if pulse monotonicity is assumed but not present. The assumption of pulse monotonicity serves to fragment larger structures and replace them with separate monotonic pieces. Using a monotonic pulse model instead of one that accounts for possible structure thus results in the recovery of more pulses, having shorter durations, and separated by smaller separations. These pieces cannot themselves have structure because any nonstochastic structure will be fragmented into smaller pulses by the monotonicity assumption. Important temporal correlations, such as the hard-to-soft spectral evolution characteristic of triple-peaked pulses, will go unrecognized and will be replaced by the less pronounced spectral characteristics of individual monotonic pulse pieces.

The Oxford English Dictionary defines complexity as “the state or quality of being intricate or complicated.” Complexity is used rather vaguely in GRB analysis to define structure in GRB light curves. We have demonstrated (Hakkila & Preece 2014; Hakkila et al. 2015) that triple-peaked residual functions are responsible for one component of GRB pulse complexity. Because of this, we are open to the idea that other, more structured variations might also be present and extractable from GRB pulses. A useful technique for classifying GRB pulses is thus one that recognizes known pulse complexities while presuming that other unknown complexities might also exist.

GRB pulse light curves of long and intermediate bursts exhibit various degrees of structure and complexity. The smooth Norris et al. (2005) pulse model works best at fitting faint long and intermediate GRB pulses; brighter pulses show evidence of more complex structures such as the triple-peaked residual function (Hakkila & Preece 2014; Hakkila et al. 2015). The existence of this nonmonotonically increasing and decreasing complexity is problematic, as pulse-fitting techniques sometimes have difficulty determining whether complexity in a GRB emission episode results from identifiable substructures or if it represents embedded fainter pulses. To complicate matters, bright emission episodes often exhibit additional chaotic variations not present in faint ones.

We note that some TTE bursts are characterized by what appear to be closely overlapping emission episodes. These are the most difficult events for us to fit because they could either represent two or more overlapping pulses or a single pulse that has an exceedingly complex temporal structure. We recognize that there will always be ambiguity in separating multipulsed emission episodes from multipeaked pulses, and we have made efforts to adequately document these ambiguous cases. It is fortunate for our analysis that the emission episodes of most TTE GRBs are clearly defined.

We approach the identification of GRB pulse complexity by assuming to first order that each isolated emission episode represents a single GRB pulse that can be fitted by the Norris et al. (2005) model. We further assume that the simplest form of complexity, representing a second-order variation in the monotonic pulse structure, is the smoothly varying triple-peaked Hakkila & Preece (2014) residual function. We use \( \chi^2 \) as our goodness-of-fit statistic to determine the effectiveness of these models, where \( \chi^2 \) indicates the normalized deviation between the data and the model relative to the degrees of freedom \( \nu \). The value of \( \chi^2 \) is dependent on the amount of nonstochastic emission (signal) relative to the amount of stochastic emission (noise) and thus to the temporal interval selected for the analysis. The number of bins (and thus the value of \( \nu \)) is sensitive to the bin size, as well as to the temporal interval. We choose the fiducial timescale for pulse analysis because it has been defined to contain most of the pulse emission.

Our previous analyses of long/intermediate BATSE, Fermi GBM, and Swift GBR pulses have found that this approach generally results in fits having \( \chi^2 \approx 1 \) in low-S/N environments consistent with stochastic variations to the model. The model is less successful for pulses showing some complexity. Many of these less well fit pulses exhibit larger precursor and/or decay peaks or additional faint residual structures that occur in addition to the residual fit. Because the Hakkila & Preece (2014) function still contributes to these pulse residuals, these findings suggest that the model is not incorrect so much as it is incomplete in accounting for augmented pulse structures.

We choose to define pulse complexity in terms of the \( \chi^2 \) \( \nu \)-values. Here \( \chi^2 \) is defined over the fiducial timescale, and \( \nu \) from the Norris et al. (2005) model is the number of temporal bins minus the number of pulse- and background-fit parameters—two for the background and four for a single pulse. The \( p \)-value associated with \( \chi^2 \) has the conventional meaning; it is the probability that a \( \chi^2 \) statistic having \( \nu \) degrees of freedom is
more extreme than the measured value. As will be seen, the pulse’s flux distribution: an optimal fit has sufficient S/N over the duration of the pulse to identify and match available structures. The burst sample is limited to 64 ms resolution outside the TTE window, which makes it difficult to fit shorter TTE partial pulses and limits the number of bins being fitted. Inside the TTE window we have chosen to use 4 ms resolution. The number of bins available for a pulse fit depends on a pulse’s duration and shape, as these quantities define the fiducial time interval. Thus, the optimal choice of a bin size is better made after a fit has been performed.

By limiting our comparisons to this fiducial interval, we minimize the chance that a good fit is obtained simply because it uses a large number of background bins, and this approach assures that the $\chi^2$ fits are generally independent of pulse duration (exceptions can occur for fiducial timescales that extend beyond the TTE window; this can have the unfortunate effect of artificially increasing $\chi^2$ by decreasing the number of available background bins). We consider good fits (indicating relatively smooth light curves) to be those having best-fit $p$-values of $p_{\text{best}} \geq 5 \times 10^{-3}$ (this is a standard choice for a "good" fit criterion). A $\Delta \chi^2$ test is used to indicate that the residual function needs to be included in the fit: $\Delta \chi^2$ is the difference in $\chi^2$ obtained from the Norris et al. (2005) model minus that obtained from the Norris et al. (2005) model combined with the Hakkila & Preece (2014) residual model. The difference in the number of degrees of freedom between these fits is four per pulse. We require a $\Delta \chi^2$-value of $p_{\Delta} \leq 10^{-3}$ for the model to be improved. This is more stringent than the criterion we use for a "good" fit because we want to ensure that the residual function, rather than some other structure, is most likely to be responsible for the improvement in the fit.

We have classified the TTE pulses into four groups using complexity as our classification parameter. We identify simple pulses as those best characterized by the Norris et al. (2005) function alone. Blended pulses are explained by the Norris et al. (2005) function but also require the Hakkila & Preece (2014) residual function to obtain a best-fit value of $p_{\text{best}} \geq 5 \times 10^{-3}$. Many pulse fits are significantly improved by the Hakkila & Preece (2014) residual function but exhibit additional unmodeled structures. This may in part result from the inability of our empirical models to explain the true evolution of the light curve. We define structured pulses as those having best-fit $p$-values of $10^{-3} \leq p_{\text{best}} < 5 \times 10^{-3}$; these pulses have many characteristics that can be explained by the pulse and residual models, but they also have statistically significant variations from these structures. The value $p = 10^{-5}$ appears somewhat arbitrary but has been selected for its potential use as a data mining attribute. This $p$-value subdivides complex pulses into two groups, such that (1) structured pulses are expected to have characteristics common with blended pulses, but also (perhaps to a lesser extent) with more complex pulses, and (2) the number of structured pulses in our sample (50) is similar to the number of blended pulses (38). The remaining pulses have complicated light curves as defined by $p_{\text{best}} < 10^{-5}$. Some of these complex pulses represent emission episodes having pronounced structures that might represent complex substructures, overlapping inseparable pulses, or a different physical phenomenon altogether. Although we have classified the TTE pulses according to these $p_{\text{best}}$ values, the BATSE TTE GRB pulse catalog includes all $p$-values so that users may adjust these classification parameters as they wish.

In addition to finding some TTE emission episodes that upon reexamination appear to be overlapping pulses, we have found a small number that do not fit the existing pulse paradigm. The final pulses in these bursts are characterized by intensities that increase with time, producing asymmetric pulse shapes that are contrary to the intensity distribution function of Norris et al. (2005). We call bursts containing these pulse structures crescendo bursts. Some, but not all, crescendo bursts are preceded by a series of short, symmetric staccato pulses. Crescendo GRBs are discussed in greater depth in Section 4.8.

Two GRBs in this sample (BATSE triggers 1626 and 7427) have been identified by Norris & Bonnell (2006) as being short GRBs with extended emission. The residuals of both of these bursts show faint emission indicative of a brightening followed by a gradual decline, which is suggestive of a faint pulse structure rather than chaotic emission. However, the S/N of this extended emission is too faint to attempt to fit with the pulse model. An additional eight short GRBs (four TTE complete and four TTE partial) are listed in Bostanci et al. (2013) as having extended emission (TTE complete triggers 575, 1719, 5592, and 5634; TTE partial triggers 3611, 3940, 7063, and 7599). Of these bursts, only trigger 575 exhibits extended emission during the TTE readout. We note that the double-pulsed nature of BATSE trigger 575 also makes it unique among the sample of short GRBs with extended emission.

We have made the light curves obtained for the residuals and combined plots available using online figure sets. The residual light curves are shown in Figure 1, while the combined light curves (pulse plus residuals) are shown in Figure 2.

Examples of representative pulse fits are shown in Figures 2–5. Figure 2 shows an example of a simple pulse (trigger 373); the left panel shows the residual structure, while the right panel shows both the Norris et al. (2005) fit (dotted line) and the combined fit (solid line). Figure 3 similarly shows a blended pulse (trigger 2896), Figure 4 shows a structured pulse (trigger 5564), and Figure 5 shows a complex pulse (trigger 4955).

The complexity classifications of all 434 pulses in our catalog are summarized in Table 2. Although the total numbers of TTE complete and TTE partial pulses are similar, the distributions of simple, blended, structured, and complex pulses are noticeably different. This is a direct result of the better temporal resolution of the 4 ms data relative to the 64 ms data. Whereas the 4 ms binning allows substructures (including separable pulses and the residual function) to be identified and fitted, the 64 ms binning merges these together and prevents them from being properly delineated for fitting. Thus, the lower-resolution partial TTE group contains more structured and complex pulses and fewer simple and blended pulses. Examination of the TTE data for the bursts in this group shows that these structures and separable pulses are present, but just not resolved in the 64 ms data (e.g., see the pulses in Figure 1).

### 3.3. Multipulsed Bursts

The vast majority of the catalog bursts (345/387 = 89\%) are single-pulsed. Most of the remainder are double-pulsed (33/387 = 9\%), and a few (3/387 = 1\%) are triple-pulsed. Six (6/387 = 2\%) are crescendo bursts, having pulse structures similar
to one another but different than that described by the standard pulse paradigm. We have likely underestimated the number of very short multipulsed GRBs having overlapping pulses because temporal resolution and pulse complexity make it hard to disentangle overlapping TTE pulses. On the other hand, our attempt to fit all sampled TTE pulses gives us confidence that we have identified most of the multipulsed TTE GRBs. Table 3 summarizes the multiplicity of TTE GRBs in this sample. A list of the multipulsed GRBs is provided in Table 4.

Although 90% of the catalog bursts are single-pulsed, we cannot unequivocally state that 90% of short GRBs are single-pulsed. Because our sample contains only short GRBs that...
entirely or mostly fit into the TTE window, we are missing the long-duration tail of the short GRB distribution (e.g., those with $T_{90} > 2$ s), and these missing bursts might well contain multiple pulses. However, we also believe that this long-duration tail is small because short bursts are separated from the other GRB classes with the most clearly delineated boundary (see Horváth 1998; Mukherjee et al. 1998; Hakkila et al. 2003), and many bursts with $T_{90} > 2$ s have the soft spectra of intermediate GRBs. Thus, we feel confident in stating that short GRBs are overwhelmingly single-pulsed.

3.4. Catalog Description

The BATSE TTE GRB pulse catalog is contained in three separate online files. Part I (Table 5) contains information related to the Norris et al. (2005) model fit. Part II (Table 6) contains information pertaining to the Hakkila & Preece (2014) residual fit (if available), descriptions of the overall pulse fit, and ancillary information such as pulse fluence and energy hardness. Part III (Table 7) contains the names of the files containing both the residual fits and the total fits to the pulse light curves, as well as comments about the pulses. These three files may be merged by the user to create a larger table, if desired.

As indicated previously, this catalog strives to systematically create a characterization of short GRB prompt emission by attempting to fit all short GRB pulses that fit entirely or partially within BATSE’s TTE window. We want to understand and characterize as many of our selection biases as we can. We believe that the selection of TTE bursts is random during the time of BATSE’s operation. We have attempted to describe uncertainties in the pulse-fitting process, as well as characterizing uncertainties in the measured pulse parameters. We have created four descriptors based on our definitions of good fits: the temporal resolution (Table 5, Column 2), the pulse complexity (Table 6, Column 22), the GRB class (Table 6, Column 20), and the decision whether or not to include the residual fit in the final best fit (Table 6, Column 16).

The comments provided in Table 7 describe a variety of characteristics that are not covered in the main catalog. These include (a) instrumental reasons why pulses have been defined as TTE partial rather than TTE complete, (b) augmented descriptions of pulse characteristics, and (c) burst or pulse properties measured elsewhere. In Table 7 we have delineated some of these complex morphologies using visual descriptions rather than formal statistical ones:

1. **Crown** pulses consist of a clearly defined single emission episode exhibiting many small peaks around the time of maximum emission;
2. **u-pulses** have u-shaped or bowl-shaped double-peaked light curves characterized by short temporal spikes at the beginning and at the end of the main emission episode, and sometimes they also have a spike at the center of the pulse;
3. **noisy double-peaked** pulses have asymmetric light curves with abnormally bright and long decay peaks;
4. **twin peaks** indicate single emission episodes having two closely separated peaks overriding the main emission.

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**Table 2**

| Pulse Complexity | TTE Complete 4 ms Resolution | TTE Partial 64 ms Resolution |
|------------------|-------------------------------|-----------------------------|
| Simple           | 133                           | 89                          |
| Blended          | 31                            | 7                           |
| Structured       | 20                            | 30                          |
| Complex          | 43                            | 71                          |
| Staccato         | 6                             | 4                           |
| Total            | 234                           | 201                         |

**Table 3**

| Burst Type       | TTE Complete 4 ms Resolution | TTE Partial 64 ms Resolution |
|------------------|------------------------------|------------------------------|
| Single-pulsed    | 180                          | 163                          |
| + extended emission | 2†                           | 0†                           |
| Double-pulsed    | 18                           | 15                           |
| Triple-pulsed    | 2                            | 1                            |
| Crescendo        | 4                            | 2                            |
| Total            | 206                          | 181                          |

Note. The extended emission GRBs identified by Norris & Bonnell (2006) show excess flux in the TTE interval. Additionally, three single-pulsed TTE complete and four TTE partial GRBs have been described by Bostanci et al. (2013) as exhibiting extended emission, along with one double-pulsed TTE complete GRB (†). Since these do not exhibit prompt extended emission, they have not been identified as extended emission bursts.

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**Figure 5.** Example of a complex short GRB pulse (trigger 4955). The left panel shows the Hakkila & Preece (2014) residual structure, while the right panel shows both the Norris et al. (2005) pulse fit (dotted line) and the combined Norris et al. (2005) pulse plus Hakkila & Preece (2014) residual fit (solid line). Complex pulses exhibit significant residual structures that cannot be explained by the Hakkila & Preece (2014) model.
The BATSE catalog publishes fluences and hardnesses for bursts, not for pulses. However, as discussed in Section 3.3, most TTE bursts appear to contain only a single emission episode, and only a few have recognizable extended emission. Thus, pulse fluences and hardnesses are generally the same as the fluences and hardnesses of the bursts in which they are found. When bursts consist of multiple pulses, modeled pulse fits are used to extract both pulse durations and energy-dependent counts fluences of constituent pulses (see, e.g., Hakkila & Preece 2011). The counts fluences are then combined with BATSE catalog data to obtain energy fluences and hardnesses for individual pulses. This modeling approach seems to produce reasonably accurate measurements of pulse duration even if pulses contain considerable structure. In other words, large $\chi^2$ uncertainty results more from poor matches to pulse structure than from difficulties in measuring pulse boundaries. The efficacy of the approach can be seen, for example, in the fits shown in Figures 2 through 6.

Using the GRB class definitions from Section 3.1, we find that short GRB pulse durations, fluences, and hardnesses correlate with one another in manners consistent with those described in Hakkila & Preece (2011) for long and intermediate GRB pulses. As expected, pulses with longer durations have correspondingly larger fluences (Figure 7, left panel). Similarly, harder pulses have correspondingly larger fluences, as high-energy photons contain significantly more energy than low-energy photons (Figure 7, right panel). A Spearman rank-order correlation test (SC) indicates that pulse fluence and duration are highly correlated ($SC = -0.31, p = 6 \times 10^{-10}$) and that hardness and fluence are even more highly correlated ($SC = 0.58, p = 7 \times 10^{-36}$). However, hardness and duration are uncorrelated ($SC = 0.46, p = 0.37$).

The amplitudes of short GRB pulses are related to their durations and fluences (Figure 8). A Spearman rank-order correlation indicates that short GRB pulse amplitude and duration are highly anticorrelated ($SC = -0.49, p = 6 \times 10^{-25}$), as are amplitude and fluence ($SC = 0.31, p = 9 \times 10^{-10}$). This relationship has been found previously for short GRBs (Hakkila & Preece 2011; Norris et al. 2011) and is itself an extension of the pulse amplitude versus duration anticorrelation found by Hakkila et al. (2008) for GRB prompt emission and known to extend to X-ray flares (Margutti et al. 2010). Using measurements of maximum count rates divided by minimum count rates on three different timescales, and comparing these measurements with pulse durations, Hakkila & Preece (2011) have demonstrated that this effect is real rather than due to a selection bias. In addition to duration and fluence, pulse hardness and amplitude (Figure 9) appear to be weakly correlated ($SC = 0.11, p = 3 \times 10^{-2}$) in short GRB pulses.

The short TTE complete and short TTE partial samples are not representative of the same underlying population owing to a sampling bias. Because TTE complete pulses fit completely within the TTE window whereas TTE partial pulses do not, TTE complete pulses tend to have shorter durations and smaller fluences than TTE partial bursts (Figure 10), as indicated by Student’s $T$-tests ($T$) comparing the logarithmic distributions of duration ($T' = -12.0, p = 2 \times 10^{-28}$) and fluence ($T' = -3.6, p = 4 \times 10^{-4}$) for short GRBs. As a result of the aforementioned anticorrelation between amplitude and duration, the difference between the TTE complete and TTE partial duration

| BATSE ID | Class | No. Pulses | Resolution |
|---------|-------|------------|------------|
| 298     | S     | 2          | 64 ms      |
| 551     | S     | 2          | 4 ms       |
| 575     | S     | 2          | 4 ms       |
| 867     | S?    | 2          | 64 ms      |
| 936     | S     | 2          | 64 ms      |
| 1453a   | S     | 4          | 4 ms       |
| 1694    | S     | 2          | 4 ms       |
| 1747    | S?    | 2          | 4 ms       |
| 2217    | S     | 2          | 64 ms      |
| 2330    | S     | 2          | 4 ms       |
| 2485    | S     | 2          | 64 ms      |
| 2715    | S     | 2          | 4 ms       |
| 2776    | S     | 2          | 64 ms      |
| 2834    | S     | 2          | 64 ms      |
| 2860    | S     | 2          | 64 ms      |
| 2861    | S     | 2          | 64 ms      |
| 2918    | S     | 2          | 4 ms       |
| 2952    | S     | 3          | 4 ms       |
| 2975    | S     | 2          | 4 ms       |
| 3173a   | S     | 2          | 4 ms       |
| 3735a   | S     | 4          | 64 ms      |
| 3736    | S     | 2          | 64 ms      |
| 3770    | S     | 2          | 4 ms       |
| 3791    | S     | 2          | 4 ms       |
| 5212    | S     | 2          | 4 ms       |
| 5439a   | T     | 3          | 4 ms       |
| 5529    | S     | 3          | 4 ms       |
| 5633    | S     | 2          | 4 ms       |
| 7273    | S     | 2          | 4 ms       |
| 7281    | S     | 3          | 64 ms      |
| 7305    | S?    | 2          | 64 ms      |
| 7375a   | S     | 2          | 4 ms       |
| 7378    | S     | 2          | 64 ms      |
| 7514    | T?    | 2          | 4 ms       |
| 7559    | T     | 2          | 64 ms      |
| 7830    | S     | 2          | 64 ms      |
| 7912    | S     | 2          | 64 ms      |
| 7943    | S?    | 2          | 64 ms      |
| 8072    | S     | 2          | 4 ms       |
| 8079    | S     | 2          | 4 ms       |
| 8120    | S     | 2          | 64 ms      |

Note. All GRBs have been classified as short (S) except triggers 5439, 7514, and 7559, which are intermediate (I).

$^a$ Crescendo GRB.

We note that some crown pulses and u-pulses have similar morphologies; it is possible that some crown pulses are merely unresolved u-pulses.

### 4. Analysis

#### 4.1. Pulse Duration, Fluence, and Hardness

Pulse energy fluences and hardnesses have been provided in the BATSE Final Catalog (https://gammaray.msfc.nasa.gov/batse/grb/catalog/current/) and are available for almost all of the TTE GRBs (a few have been obtained from Goldstein et al. (2013) and are identified in Table 7). For this analysis we define energy hardness as

$$HR = (S_3 + S_4)/(S_1 + S_2),$$  

where $S_n$ refers to the fluence in BATSE energy channel $n$. 

The counts fluences for individual pulses contained in the burst are then combined with the BATSE catalog data to obtain energy fluences and hardnesses for individual pulses.
### Table 5
Information Contained in the BATSE TTE GRB Pulse Catalog (Part I)

| Table Column | Header       | Variable     | Units     | Description                                                                 |
|--------------|--------------|--------------|-----------|-----------------------------------------------------------------------------|
| 1            | pulse_id     | BATSE trigger| number (+ letter) | number (+ letter)                                                             |
| 2            | resolution   | resolution   | ...        | 4 ms for TTE complete or 64 ms for TTE partial                               |
| 3            | B            | B_0          | counts     | mean background per bin                                                      |
| 4            | B_err        | σ_{B_0}      | counts     | mean background uncertainty per bin                                          |
| 5            | BS           | BS           | counts s^{-1} | background rate change per bin                                               |
| 6            | BS_err       | σ_{BS}      | counts s^{-1} | background rate change uncertainty per bin                                   |
| 7            | ts           | τs           | s          | pulse start time, from Equation (1)                                          |
| 8            | ts_err       | σ_{τs}      | s          | pulse start time uncertainty                                                 |
| 9            | A            | A            | counts     | pulse amplitude, from Equation (1)                                           |
| 10           | A_err        | σ_{A}       | counts     | pulse amplitude uncertainty                                                 |
| 11           | τ1           | τ_1          | s          | pulse rise parameter, from Equation (1)                                     |
| 12           | τ1_err       | σ_{τ_1}     | s          | pulse rise parameter uncertainty                                             |
| 13           | τ2           | τ_2          | s          | pulse decay parameter, from Equation (1)                                    |
| 14           | τ2_err       | σ_{τ_2}     | s          | pulse decay parameter uncertainty                                             |
| 15           | w            | w            | s          | pulse duration, from Equation (3)                                            |
| 16           | w_err        | σ_{w}       | s          | pulse duration uncertainty                                                  |
| 17           | kappa        | κ            | ...        | pulse asymmetry, from Equation (4)                                           |
| 18           | kappa_err    | σ_{κ}       | ...        | pulse asymmetry uncertainty                                                 |
| 19           | τ_peak       | τ_{peak}    | s          | pulse peak time, from Equation (2)                                           |
| 20           | τ_peak_err   | σ_{τ_{peak}}| s          | pulse peak pulse time uncertainty                                           |
| 21           | t_start      | τ_{start}   | s          | fiducial start time, from Equation (7)                                       |
| 22           | t_end        | τ_{end}     | s          | fiducial end time, from Equation (6)                                         |
| 23           | χ^2          | χ^2         | ...        | goodness of fit for pulse + background model                                 |
| 24           | nu           | ν            | ...        | degrees of freedom for fit for pulse + background model                       |
| 25           | chi^2_nu     | χ^2_nu      | ...        | reduced goodness of fit for pulse + background model                         |

(This table is available in its entirety in machine-readable form.)

### Table 6
Information Contained in the BATSE TTE GRB Pulse Catalog (Part II)

| Table Column | Header       | Variable     | Units     | Description                                                                 |
|--------------|--------------|--------------|-----------|-----------------------------------------------------------------------------|
| 1            | pulse_id     | BATSE trigger| number (+ letter) | number (+ letter)                                                             |
| 2            | t0           | t_0          | s          | residual peak time, from Equation (5)                                       |
| 3            | t0_err       | σ_{t_0}     | s          | residual peak time uncertainty                                              |
| 4            | a            | a            | counts     | residual amplitude, from Equation (5)                                       |
| 5            | a_err        | σ_{a}       | counts     | residual amplitude uncertainty                                              |
| 6            | omega        | ω            | s^{-1}      | residual Bessel frequency, from Equation (5)                                |
| 7            | omega_err    | σ_{ω}       | s^{-1}      | residual Bessel frequency uncertainty                                       |
| 8            | s            | s            | ...        | Bessel function stretching parameter, from Equation (5)                     |
| 9            | s_err        | σ_{s}       | ...        | Bessel function stretching parameter uncertainty                            |
| 10           | χ^2          | χ^2         | ...        | goodness of fit for pulse + residual + background model                      |
| 11           | ν            | ν            | ...        | degrees of freedom for pulse + residual + background model                   |
| 12           | chi^2_nu     | χ^2_nu      | ...        | reduced goodness of fit for pulse + residual + background model              |
| 13           | delta_chi^2  | Δχ^2        | ...        | goodness-of-fit improvement from residual model                             |
| 14           | delta_nu     | Δν          | ...        | difference in degrees of freedom                                            |
| 15           | p_delta      | p_Δ         | ...        | p-value of model improvement                                                |
| 16           | include      | include      | ...        | “x” to include residuals, “o” to exclude, based on p_Δ                     |
| 17           | R            | R            | ...        | ratio of A/u, from Equation (13)                                            |
| 18           | 4 ms_pk_cts  | 4 ms peak counts | counts | measured peak counts per bin                                               |
| 19           | 4 ms S/N     | 4 ms S/N     | ...        | S/N from Equation (14)                                                      |
| 20           | burst_class  | burst class  | ...        | GRB class from Section 3.1 and summarized in Table 1                        |
| 21           | p_best       | p_{best}    | ...        | best-fit p-value                                                            |
| 22           | pulse_class  | pulse class | ...        | pulse classification, described in Section 3.2                             |
| 23           | S            | S            | erg cm^{-2} | energy fluence from BATSE catalog and pulse fits                            |
| 24           | S_err        | σ_{S}       | erg cm^{-2} | energy fluence uncertainty                                                  |
| 25           | HR           | HR           | ...        | energy hardness from Equation (15)                                          |
| 26           | HR_err       | σ_{HR}      | ...        | energy hardness uncertainty                                                 |

(This table is available in its entirety in machine-readable form.)
distributions reflects a difference between the amplitude distributions. This can be seen in Figure 11 and in the Student’s $T$-test results \((T = 5.8, p = 10^{-8})\). A similar result has been previously identified by Norris et al. (2011) for short Swift GRB pulses.

These results demonstrate that the overall distribution of short GRB pulse properties cannot be described using TTE complete pulses alone. Instead, the different properties of TTE partial pulses must be included. Even when these have been included, the combined TTE sample is not entirely representative of the underlying short GRB pulse distribution. Only a small fraction of bursts in this sample have been formally classified as long/intermediate GRBs, suggesting that the long-duration end of the short GRB sample cannot be sampled by the durations of TTE windows.

### 4.2. Short GRBs Exhibit a Continuum of Pulse Complexity

The pulse classes defined in Section 3.2 in terms of complexity represent a continuum of characteristics; our definition of four discrete groups is somewhat arbitrary. Figure 12 demonstrates where the simple (crosses), blended (asterisks), structured (diamonds), and complex (triangles) groups are found in terms of their fit improvement by the residual function \((p_\Delta)\) and their final best fit \((p_{\text{best}})\) for both the TTE complete (blue) and TTE partial (red) samples. The vast majority of the pulses lie in the upper right corner (large best-fit \(p\)-values and large \(\Delta \chi^2\) \(p\)-values); these simple pulses are well characterized using only the Norris et al. (2005) pulse model. Blended TTE complete pulses along the top of the graph (large best-fit \(p\)-values but small \(\Delta \chi^2\) \(p\)-values) are best fit by the Norris et al. (2005) model combined with the Hakkila & Preece (2014) residual model. Structured TTE complete pulses (small best-fit \(p\)-values) are too complex to be completely characterized using combinations of the Norris et al. (2005) and Hakkila & Preece (2014) pulse models, but there is a gradual change in complexity from blended, to structured, to complex pulses. Many TTE partial pulse light curves cannot adequately be explained by the Norris et al. (2005) pulse function alone, but the temporal binning of these light curves provided too few data points for any residual structure to be identified.

### 4.3. Internal Errors: Comparing Pulse Properties Measured with Both 4 and 64 ms Resolution

Eighty-five pulses have been fitted using both 4 ms and 64 ms data. Although 64 ms data provide inadequate temporal resolution for fitting most residuals (described previously), the bulk observable Norris et al. (2005) pulse properties (amplitude \(A\), duration \(w\), and asymmetry \(\kappa\)) have been measured using data from both timescales. These properties can be directly compared to provide an internal check on the reliability of the pulse-fitting process and also to provide insights into the measurement uncertainties of these properties as determined by the MPFIT.PRO nonlinear least-squares routine (Markwardt 2009).

The 64 ms timescale pulse amplitudes \((A_{64})\) are compared to their 4 ms pulse counterparts \((A_{4})\) in the left panel of Figure 13. The majority of these amplitudes are highly correlated, and a Spearman rank-order correlation test indicates that these amplitude measurements are highly correlated \((SC = 0.77, p = 6 \times 10^{-15})\). However, a few pulse amplitudes are found to differ systematically by large amounts, while a few others have abnormally large statistical uncertainties. The systematically different measurements all have uncertainties of \(\sigma_{A} = 0\), and all but one of these values have been measured on the 64 ms timescale. In fact, both the large and small uncertainties are associated with large-amplitude pulses having short durations relative to the bin size. We conclude that the nonlinear least-squares routine has difficulty converging at the intensity inflection point when a limited number of data points are present to describe large intensity variations. Upon excluding 32 pulses having either very large \((\sigma_{A_{64}} \geq 5 \times A_{4})\) and \(\sigma_{A_{64}} \geq 5 \times A_{4}\) or small \((\sigma_{A_{64}} = 0\) and \(\sigma_{A_{4}} = 0\) measurement uncertainties, the expected relationship is recovered and shown in the right panel of Figure 13. Although most of these measurements are consistent with unity, many 64 ms amplitudes are slightly smaller than their 4 ms counterparts.

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**Table 7**

| Pulse ID | Comments |
|----------|----------|
| 138      | probably single emission episode, but could be two overlapping |
| 185      |          |
| 206      |          |
| 218      | possible crescendo burst without staccato pulses |
| 289      |          |

(This table is available in its entirety in machine-readable form.)
This results because the 64 ms binning washes out some of the 4 ms pulse structure.

The 64 ms timescale pulse durations \( w_{64} \) are compared to their 4 ms pulse counterparts \( w_{4} \) in the left panel of Figure 14. The duration measurements are highly correlated \( (SC = 0.92, p = 7 \times 10^{-36}) \), even though the individual measurement uncertainties are large. In other words, there do not appear to be systematic differences between durations measurements made using fits on different timescales. As expected, relative uncertainties \( \sigma_{w}/w \) increase as pulse durations approach the temporal resolution. Limiting the sample to durations measured accurately on both timescales demonstrates the consistency of fitting on the two different timescales; this is shown in the right panel of Figure 14 for 42 pulses having \( \sigma_{w} \lesssim w \).

Finally, the 64 ms pulse asymmetries \( \kappa_{64} \) are compared to their 4 ms counterparts \( \kappa_{4} \) in the left panel of Figure 15. Figure 15 demonstrates that asymmetry measurements are difficult to make on the short GRB timescales, as large uncertainties accompany the measurements for many of the pulses. However, a Spearman rank-order correlation test indicates that the asymmetry measurements are weakly correlated \( (SC = 0.24, p = 0.07) \). This correlation can be clarified by limiting the sample to accurately measured pulses. The right panel of Figure 15 shows that both 64 ms and 4 ms resolutions measure similar asymmetries when the sample is limited to those pulses having accurate measurements \( (\sigma_{\kappa} \lesssim 0.15) \).

It appears that the formal fitting process has led to overestimates of many uncertainties for \( \sigma_{w} \) and \( \sigma_{\kappa} \). Through inspection it appears that many \( \sigma_{\kappa} \) measurements have also been overestimated. The uncertainties for these observables were propagated from the fitted values of \( \sigma_A, \sigma_{\tau_0}, \sigma_{\tau_1}, \) and \( \sigma_{\tau_{\text{full}}} \). Although the fitted variables are generally not observable (with the exception of \( A \)), the uncertainties in the measurement of many of these variables also seem to be inordinately large.

The mathematical expression describing the Norris et al. (2005) intensity model (Equation (1)) has several characteristics...
Figure 10. Logarithmic pulse duration (left panel) and fluence (right panel) histograms for short TTE GRBs in this catalog. TTE complete pulse distributions are indicated by solid lines, and short TTE partial pulses are indicated by dashed lines.

Figure 11. Logarithmic pulse amplitude histograms for short TTE GRBs in this catalog. TTE complete pulses (solid line) have larger pulse amplitudes than TTE partial pulses (dashed line).

that make it difficult to fit. The largest signal exists at time $\tau_{\text{peak}}$, when the pulse intensity equals the amplitude $A$ and where exponentially increasing and decreasing intensity functions involving $\tau_1$ and $\tau_2$ are joined. The start and end of the pulse provide few additional helpful fitting constraints: $t_s$ occurs when the pulse rise intensity equals the background at the beginning of the pulse ($I_s$ prevents the intensity function from going to infinity prior to the pulse’s beginning), the exponential rise $\tau_1$ determines how fast the intensity increases from $I_s$, and the exponential decay of $\tau_2$ describes the rate of intensity decrease while ensuring that this intensity will never quite reach the background.

The interplay between $\tau_1$, $\tau_2$, and $A$ constrains the pulse rise, while the interplay between $\tau_1$, $\tau_2$, and $A$ constrains the pulse peak. These pulse parameters are harder to fit when the temporal resolution is poor, as there are fewer intensity points available with which to describe the intensity function.

Very large and very small values of $\tau_1$ and $\tau_2$ are particularly hard to constrain. A small $\tau_1$ value indicates a slow pulse rise, while a large value indicates a rapid rise producing a correspondingly early pulse start time $t_s$. A small $\tau_2$ value indicates a rapid pulse decay, while a large $\tau_2$ value indicates a slow pulse decay. Pulse fits resulting in these large and/or small $\tau_1$ and $\tau_2$ values are often accompanied by fitting uncertainties exceeding the measured value by an order of magnitude or more. This most often happens in pulses that are short relative to the temporal resolution, as these occur where the rates of intensity rise and fall are masked by the temporal bin size.

When the $\tau_1$ rise and $\tau_2$ decay components of this function are well behaved ($10^{-3} \approx \tau_1 \approx 10^3$ and $10^{-3} \approx \tau_2 \approx 10^3$), smoothly varying functions result and the $\tau_1$ and $\tau_2$ distributions seem to be normally distributed. Very large or very small pulse rise and decay values produce uncertainty distributions that appear to be asymmetric.

Increased temporal resolution improves the quality of both the pulse fits and measured pulse parameters. For this reason, the formal pulse-fitting parameters obtained from the 4 ms TTE complete sample have smaller formal uncertainties than their 64 ms TTE partial counterparts. However, constraints are
present for all pulses in the TTE pulse catalog as a result of poor counting statistics: the higher TTE resolution results in fewer counts per bin, which provides its own limits on pulse property measurement.

The formal duration errors obtained from MPFIT can be compared to the internal error distribution taken from the differences between \( w_4 \) and \( w_{64} \). In other words,

\[
\sigma_{w_{64} - \text{internal}} = |w_4 - w_{64}|/\sqrt{2}.
\]

We find that the internal and external duration error distributions are consistent with one another such that

\[
\sigma_{w_{64} - \text{internal}}^2 \approx \sigma_{w_4}^2 + \sigma_{w_{64}}^2
\]

upon excluding pulses with poorly measured durations (\( \sigma_{w_64} \geq 10 \) s and \( \sigma_{w_{64}} \geq 10 \) s). It should also be noted that duration uncertainties increase for faint pulses (as measured both by fluence and by peak flux). This is not surprising, as the
duration definition (given in Equation (3)) is dependent on intensity.

4.4. Pulse Complexity as a Function of Signal-to-noise Ratio

Some pulse complexity appears to result from a selection bias stemming from inadequate temporal resolution; this can be found by examining the different numbers of events in each of the pulse complexity classes (see Table 2). Far more TTE complete pulses can be characterized by the Norris et al. (2005) pulse function plus the Hakkila & Preece (2014) residual function than TTE incomplete pulses. In other words, poor temporal resolution appears to have created false pulse structures by rebinning and smearing out the known triple-peaked pulse characteristics.

Once we exclude TTE partial pulses from our sample, we find that bright GRB pulses tend to have more complex structures than faint pulses, in agreement with previous results obtained for long/intermediate GRB pulsars (Hakkila & Preece 2014; Hakkila et al. 2015). We characterize the TTE complete sample by a 4 ms definition of S/N (see Equation (14)). Figure 16 demonstrates that pulse complexity (characterized by the best-fit $p$-value $p_{\text{best}}$) increases as S/N increases. The correlation between these characteristics is significant (a Spearman rank-order correlation analysis finds $SC = 0.48$, $p = 6 \times 10^{-15}$). Figure 16 shows that simple and blended pulses are the faintest, structured pulses are brighter, and complex pulses are the brightest. We draw several conclusions from Figure 16:

1. Short GRB pulses, like their long and intermediate burst counterparts, exhibit a triple-peaked structure.
2. A smaller percentage of short GRB pulses seem to exhibit measurable residual structure (blended and structured) compared to long/intermediate GRBs, although it is difficult to imagine what a complete sample of long/intermediate burst pulses should look like based on existing analyses.
3. The triple-peaked structure is less pronounced for low-S/N GRB pulses (see Figure 16), suggesting a sampling bias by which structure might be present in most or all pulses but cannot be resolved with low photon counts.

4. More pronounced pulse structures are observed at high S/N (as denoted by the relative number of structured and complex pulses), suggesting that most or all GRB pulses contain complex structures, but these also are washed out at low S/N.

GRB pulses are difficult to resolve and to fit at low S/N, resulting in less certain measurements of their properties relative to bright pulses. This can have the undesired effect of altering pulse properties near the S/N threshold. Figure 17 demonstrates that faint TTE pulse properties do indeed differ from those of bright pulses, as measured by $R$ (the ratio of the residual fit amplitude to the pulse fit amplitude; see Equation (13)) relative to S/N. We find the following:

1. Pulses characterized by large complexities (structured and complex) are observed at larger S/N than those having simpler structures (simple and blended). See Table 8.
2. Pulses with large residual structures ($R > 0.8$) are primarily found near the minimum S/N threshold. See Figure 17.
3. Pulses observed at the largest S/N have the smallest measured $R$ values. See Figure 17.

The light curves of bright TTE pulses exhibit more pronounced structural complexity than the smooth light curves of fainter pulses. Some of this can be explained by the simple observation that noise is capable of washing out pre-existing pulse structures and making pulse light curves look smoother. However, the large S/N range spanned by pulses suggests that there might also be an intrinsic effect such that bright pulses
indicating asymmetry in their residual function, have larger values of \( \Omega \), correspondingly shorter residual functions. Right panel: Bessel function frequency versus faint ones. Such a conclusion is consistent if a pulse lag only be explained if bright pulses are also more luminous than exhibit larger temporal variabilities than faint ones. Such a conclusion is consistent if a pulse lag versus pulse luminosity relationship exists for short GRBs that is analogous to the relationship identified previously for long ones (e.g., Hakkila et al. 2008).

4.5. Complexity in Blended and Structured Pulses: Characterizing the Residual Function

The addition of the residual function improves many of the short GRB pulse fits. The wavelike form of the residual function, which can be described by a modified Bessel function attached to a compressed mirror image of itself, produces a rippled or multipeaked shape to the otherwise monotonic underlying pulse. The multipeaked shape is common among the isolated pulses in long/intermediate bursts detected by BATSE, Swift, and Fermi GBM (Hakkila & Preece 2014; Hakkila et al. 2015), and the characteristics of the residual function correlate with a number of other pulse properties.

The residual function is generally confined to the temporal interval occupied by the underlying pulse: the duration of the residual function (characterized by the Bessel frequency \( \Omega \)) correlates with the pulse duration \( (w) \), which is similar to results found for long/intermediate GRB pulses (Hakkila & Preece 2014; Hakkila et al. 2015). The left panel of Figure 18 demonstrates this correlation (SC = −0.80, \( p = 6 \times 10^{-28} \)).

For long/intermediate GRB pulses, the inherent asymmetry of the residual function (characterized by \( s \)) anticorrelates with the pulse asymmetry \( (\kappa) \), indicating that the residual structure is aligned with the underlying pulse shape. Unfortunately, a similar correlation cannot be verified for short GRB pulses (SC = −0.35, \( p = 2 \times 10^{-2} \) is found), as the low-S/N environment in which these pulses are found makes accurate \( \kappa \) measurements difficult.

An anticorrelation is found between \( \Omega \) and \( s \) (demonstrated in the right panel of Figure 18, with a Spearman rank-order correlation of SC = 0.46, \( p = 8 \times 10^{-6} \)). This is surprising because this correlation suggests that duration \( (w) \) and asymmetry \( (\kappa) \) are related, whereas no correlation is found \( (p = 0.82) \). We suspect that this correlation is not entirely real; it might result from the low-S/N environment in which short GRB pulses are found, the potentially interdependent ways in which \( \Omega \) and \( s \) contribute to the residual function in Equation (8), and the fact that our initial estimates of \( \Omega \) and \( s \) are based on \( \kappa \).

The peak time of the residual function \( t_0 \) is found to not always align with the peak time of the underlying pulse \( \tau_{\text{peak}} \). This is demonstrated in Figure 19, where the difference \( t_0 - \tau_{\text{peak}} \) has been normalized to a standard time by dividing it by the pulse duration \( w \). Although this offset appears to be real, the reason for the offset (which is positive for some bursts and negative for others) is still not understood, because it implies that the pulse and the residual function are somewhat independent of one another.

The amplitude of the residual function \( (a) \) varies from near zero to roughly the pulse amplitude \( (A) \); the ratio of these amplitudes is characterized by \( R \). However, we find no obvious correlation between the normalized difference and the alignments of \( t_0 \) and \( \tau_{\text{peak}} \) with other pulse parameters (e.g., \( R, HR, S \)).

4.6. Pulse Spectral Evolution

Long/intermediate GRB pulse light curves evolve from hard to soft, with rehardening occurring at or just prior to each of the
three pulse peaks (Hakkila et al. 2015). Asymmetric pulses are hard overall and have pronounced hard-to-soft evolution; these contrast with symmetric pulses that are softer and have weak hard-to-soft evolution. This weak evolution can result in softer precursor peaks than central peaks, giving pulses the appearance of having intensity tracking behaviors.

It is interesting to see whether short GRB pulses undergo similar spectral evolutions to long/intermediate GRB pulses. Finding that they do would independently validate our initial assumption that short GRB emission episodes are indeed individual pulses, because we made no spectrally dependent assumptions about spectral evolution in our pulse definition (see 2.2).

The TTE pulse light curves have been collected in the four energy channels, described previously. Although the count rates in each of these four channels are low, they provide some information that can be used to infer pulse spectral evolution. We define the counts hardness ($hr$) in each time bin $i$ as

$$hr_i = \frac{C_{3i} + C_{4i}}{C_{1i} + C_{2i}}, \quad (18)$$

where $C_{1i}$, $C_{2i}$, $C_{3i}$, and $C_{4i}$ are the counts per bin in channels 1, 2, 3, and 4, respectively. We track 4 ms pulse spectral evolution by measuring $hr_i$ in each bin between $t_{\text{start}}$ and $t_{\text{end}}$, in a manner similar to that done in Hakkila et al. (2015) for BATSE and Swift data.

We sum the counts from many pulses to get summed light curves and spectral evolution averages; this approach overcomes limits imposed by small number counting statistics and allows us to examine spectral evolution as a function of pulse structure. (Note: we have excluded pulses with negative total hardness ratios, as well as pulses with trigger numbers between 3282 and 3940 having incorrectly transcribed channel 1 counts data). Figure 20 shows the normalized mean light curve (solid line) and $hr$ evolution (dashed line) for all 159 BATSE TTE complete pulses (left panel). Also shown are normalized mean light curves (solid lines) and counts hardness evolutions (dashed lines) of long/intermediate BATSE pulses (left panel) and long/intermediate Swift pulses (right panel).

It is not surprising that the summed light curves exhibit the triple-peaked structure, as the light curves have been co-added using this structure as a temporal template. However, this co-adding should not produce the observed hard-to-soft pulse evolution, with spectral rehardening occurring at or just before each of the three peaks. This behavior is similar to that seen in long/intermediate GRB pulses, independently demonstrating that these short GRB emission episodes are individual pulses.

The normalized mean light curves verify the hypothesis that each emission episode contains but a single pulse. This appears to be true even for structured and complex pulses, where highly variable light curves are co-added to produce smooth light curves exhibiting only the triple-peaked structure. The rapidly varying component does not alter the underlying hard-to-soft spectral evolution, which is similar to that found in simple and blended pulses. However, structured/complex pulses appear to be harder than smoother pulse types, suggesting that the highly variable component is responsible for this. This result leads us to two important conclusions: (1) despite their highly variable structures, complex emission episodes are also single pulses, and (2) the highly variable component found in structured/complex pulses contains higher-energy photons than what is found in the smoothly evolving component.

This verification leads us to draw an additional important conclusion: structure and complexity beyond the triple-peaked pulse shape represent an additional, randomly distributed emission component that is not present in all short GRB pulses. Summing together a large number of structured and complex pulses should itself produce a complex light curve rather than the triple-peaked structure seen in the right panel of Figure 21. As described in the previous paragraphs, this additional emission component is bright, hard, and variable.

4.7. Multipulsed Short GRBs

Although multipulsed TTE bursts are uncommon (making up only 10% of the population), their light curves are interesting because they contain interpulse separations as well as pulse durations. For multipulsed GRBs we define the interpulse separation ($w_{\text{sep}}$) as

$$w_{\text{sep}} = \tau_{\text{peak2}} - \tau_{\text{peak1}}. \quad (19)$$
where $\tau_{\text{peak}1}$ and $\tau_{\text{peak}2}$ are the times of maximum amplitude for pulses 1 and 2, respectively. The $T_{90}$ duration of a two-pulsed GRB is thus

$$T_{90} \approx \tau_{\text{rise}} + w_{\text{sep}} + \tau_{\text{decay}},$$

where $\tau_{\text{rise}}$ is the rise time of the first pulse and $\tau_{\text{decay}}$ is the decay time of the second pulse. Since $w_{\text{sep}}$ is generally larger than the durations of either pulse, the $T_{90}$ duration of a GRB is generally dominated by the interpulse separation (see, e.g., Hakkila et al. 2003). Measurements of $w_{\text{sep}}$ allow us to explore relationships between emission times of pulses in multipulsed GRBs, as well as the pulsed emission itself.

Strong correlations exist between the times of the emission episodes and the intervals separating them. The left panel of Figure 23 demonstrates that interpulse separations strongly correlate with first pulse durations; a Spearman rank-order test finds $SC = 0.78$ and $p = 6 \times 10^{-8}$. This correlation indicates that longer energy release times in the first pulse introduce correspondingly longer wait times until energy is released in the next pulse. The right panel of Figure 24 shows that the second pulse’s duration is also longer when the first pulse’s
duration is long; a Spearman rank-order correlation test finds $SC = 0.60$ and $p = 2 \times 10^{-4}$. This correlation indicates that the energy release time of the second pulse lasts longer when the energy release time of the first pulse is also long.

Even though few GRB redshifts were available during the BATSE era, the three durations we have measured independently in each burst ($w_1$, $w_2$, and $w_{sep}$) can provide us with sufficient information to develop two redshift-independent parameters. We define these parameters by dividing the second pulse’s duration and the burst’s interpulse separation by the corresponding first pulse’s duration. Since all three parameters are time dilated by the same factor $1 + z$ (where $z$ is the redshift), the ratios $w_2/w_1$ and $w_{sep}/w_1$ are redshift independent. Figure 24 demonstrates the intrinsic correlation between $w_2/w_1$ and $w_{sep}/w_1$ ($SC = 0.67$, $p = 2 \times 10^{-5}$). This correlation demonstrates a lengthening of the observed emission episodes coupled with a lengthening of the waiting time between these episodes.

Pulse durations and interpulse separations are not independent quantities: later pulses have memories of at least some properties of the initial pulses, as well as of the gaps separating the pulses. If pulses represent structures undergoing kinematic motion, then a long pulse duration indicates that the pulsed emission occurs over a large distance. Similarly large interpulse gaps indicate either a large distance between locations where a pulse occurs or a deceleration in the bulk flow velocity. One interpretation of the increase in duration between the second pulse and the first pulse would then be that the emitting material has slowed and/or lost energy. This could be the result of jet expansion and/or slowing of the bulk flow.

### 4.8. Crescendo GRBs

As described in Table 2, four of the TTE bursts have pulse structures that are inconsistent with the standard GRB pulse paradigm. These bursts are instead characterized as asymmetric structures that increase gradually in intensity and then end with an abrupt crescendo (see Table 9). The individual pulse structures leading to the crescendo are clearly visible for triggers 3735 and 5439 (Figure 25), whereas they are unresolved for triggers 1453 and 3173 (Figure 26) and trigger 7375 (Figure 27). Because the bursts all increase in intensity with time, we refer to these gamma-ray transients as crescendo bursts and the rapid-fire pulses as staccato pulses. Our limited temporal resolution, coupled with the fact that trigger 5439 is an intermediate GRB, prohibits us from determining whether there is more than one category of crescendo bursts.

In reevaluating the pulses in the BATSE TTE pulse catalog with this new definition in mind, we notice that the pulses associated with triggers 218 and 7753 also exhibit possible crescendo behavior. We have identified these pulses as possible crescendo bursts in the Comments column of the catalog (Table 7).

Although GRB pulse structure provides minimal evidence that short and long GRBs have different progenitors, crescendo GRBs with staccato pulses exhibit signatures of emission predicted from neutron star–black hole mergers. Tidal disruption of the neutron star is expected in a coalescing system of this type, forming a torus around the black hole. Tidal disruption should cause the torus to precess via Lense–Thirring torques (Stone et al. 2013), resulting in a signal consisting of a small number of quasi-periodic events with interpulse separations of around 30–100 ms. The predicted precession period $T_p$ should increase as $T_p \propto t^{1/3}$, leading to a corresponding increase in the interpulse separation. The separations between the staccato pulses in BATSE triggers 3735 and 5439 exceed the expected 30 to 100 ms window, and these separations do not increase as $t^{1/3}$, so it seems unlikely that these crescendo bursts are consistent with the neutron star–black hole merger model. However, the variable emission in crescendo bursts 1453, 3173, and 7375 is of a shorter timescale and may be consistent with the model, although this is undetermined owing to the unresolved temporal binning. Regardless, the rarity of bursts having nonpulsed emission of the type predicted by Stone et al. (2013) is in agreement with the results of

![Figure 24. Redshift-independent characteristics of double-pulsed short GRBs. A Spearman rank-order correlation value of $p = 5 \times 10^{-5}$ demonstrates a lengthening of the observed emission episodes coupled with a lengthening of the waiting time between these episodes.](image-url)

| TTE Crescendo Bursts | Description |
|----------------------|-------------|
| 1453                 | 4–5 overlapping peaks increasing in intensity to a short bright final pulse |
| 3173                 | 4–5 overlapping peaks increasing in intensity to a long, bright final pulse |
| 3735                 | 3–4 symmetric short staccato constant-intensity pulses followed by a longer, final bright pulse |
| 5439                 | TTE partial bursts: overlapping peaks increasing in intensity to a short bright final pulse |
| 3904                 | 2 symmetric short staccato pulses followed by a bright symmetric pulse |
| 7375                 | 7–8 overlapping peaks increasing in intensity |

Example of a possible long crescendo burst?

| 1425 | 5–6 symmetric overlapping staccato pulses increasing in intensity |

Table 9: BATSE Crescendo Bursts
Dichiara et al. (2013), who find that events having these predicted properties do not dominate the short GRB population. Not all crescendo bursts necessarily belong to the short GRB class. At least one long GRB (BATSE trigger 1425; Figure 28) appears to exhibit crescendo behavior along with staccato pulses. However, it should be noted that pulses in this burst appear to have asymmetric shapes consistent with the Norris et al. (2005) pulse model, unlike the pulses in the crescendo GRBs 3735 and 7375.

5. Conclusions

Pulses are the dominant structures in short GRB light curves, as they are in long and intermediate GRBs. We have verified this by producing a catalog of BATSE TTE GRB pulses and their properties; the vast majority of bursts in this catalog belong to the short GRB class. The catalog has been compiled under the assumption that most GRB emission structures can be explained to first order by the Norris et al. (2005) empirical

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Figure 25. Crescendo GRBs 3735 (left panel) and 5439 (right panel). These bursts contain staccato pulses.

Figure 26. Crescendo GRBs 1453 (left panel) and 3173 (right panel). Temporal resolution makes it difficult to tell whether these bursts contain staccato pulses.

Figure 27. Crescendo GRB 7375 (left panel) and TTE partial crescendo GRB 3904 (right panel). The crescendo structure of 3904 cannot be seen in 64 ms data and is only clearly seen in 4 ms data when comparing energy-dependent light curves. Light curves in BATSE energy channels are identified by different colors: channel 1 (red; 25–50 keV), channel 2 (yellow; 50–100 keV), channel 3 (green; 100–300 keV), and channel 4 (blue; 300 keV–1 MeV).
The catalog contains 434 pulses in 387 GRBs, characterized by those fit at 4 ms resolution and those fit at 64 ms resolution.

Statistical and machine learning tools form the basis of the approach used to construct the pulse catalog. The identification of short GRBs is based on statistical clustering methods and has been extended to this data set using supervised classification, rather than from using the common but more arbitrary $T_{90} < 2$ s rule. Pulse light curves and pulse residuals are fitted to empirical models with flexible parameters using a nonlinear least-squares modeling approach. An iterative, heuristic statistical approach is used both to characterize pulses that are likely to be pulses, and they help us to characterize complexity. We have binned flux data in order to apply pulse and residual models, and we have demonstrated that the temporal resolution of our binned data affects our ability both to identify pulses and to characterize their complexities. $S/N$ plays a similar role to binning in washing out existing structure. Both of these effects must also be considered when comparing pulses observed by gamma-ray detectors having different sensitivities, spectral responses, and temporal resolutions (e.g., Swift, Fermi GBM, Suzaku).

Most short GRB pulses exhibit correlated behaviors suggesting that they are produced by mechanisms governed by only a few free parameters. These processes, whatever they are, seem to be responsible for producing not just short pulses but also pulses found within all GRB classes. Among these correlated properties: shorter-duration pulses have higher amplitudes (peak fluxes) than longer-duration pulses, higher-flux pulses also have harder spectra than faint ones, and higher-flux pulses have higher amplitudes than lower-flux ones. These correlated properties are common among short, intermediate, and long GRBs, thus linking all three burst classes and suggesting similar emission mechanisms. Unlike in long and intermediate burst pulse evolution (Hakkila & Preece 2014; Hakkila et al. 2015), the role of asymmetry in short GRB pulses is difficult to determine because asymmetry is difficult to measure given the small number of photons detected.

The triple-peaked behavior seen in long/intermediate GRB pulses is also present in short GRB light curves, which exhibit a continuum of structural complexity. The simplest form can be modeled by a monotonically increasing and decreasing pulse structure (Norris et al. 2005). A slightly more complex pulse shape is nonmonotonic but still smooth; we represent this with the Norris et al. (2005) pulse model augmented by the Hakkila & Preece (2014) residual structure. Additional structural complexity appears to be added on top of the Norris et al. (2005) pulse model plus Hakkila & Preece (2014) residual model; these pulses have excess complex emission overlaying a recognizable triple-peaked structure. The most complex pulses are dominated by complex and chaotic structures; they are only recognizable as pulses because their chaotic structure is found within a single emission episode. Not all of this complex structure is chaotic; many complex pulses exhibit what appear to be recognizable and repeated behaviors that suggest the existence of complex pulse subclasses. However, composite light curves made by summing the fluxes of many complex pulses show only the smooth triple-peaked structure, validating our hypothesis that complexity represents a randomly distributed augmentation of the light curve.

The triple-peaked pulse behavior is supportive of emission from a shocked medium (Hakkila & Preece 2014), with the mirroring effect seen in the precursor and decay peaks suggesting forward and reverse shock behavior. The hard-to-soft evolution observed in GRB pulses also indicates that the time of maximum energy release is at the beginning of the pulse, when the light-curve intensity is still increasing. The additional structure seen in the light curves of structured and complex pulses may indicate GRBs in which additional, more chaotic radiation processes are also involved. These chaotic patterns are only present in conjunction with preexisting pulse light curves, further supporting the idea that pulses are the underlying, foundational units of GRB emission. The additional complex structures might represent some more localized behavior, such as microjets or electromagnetic fluctuations of some sort.

Double- and triple-pulsed short GRBs are uncommon, but they exist. These bursts provide valuable insights into the processes by which GRBs release energy. The interpulse separations in these multiple-pulsed bursts correlate with the duration of the initial pulse, suggesting that first-pulse duration is a predictor for the time that will pass before the next pulse is emitted. Similarly, the duration of the second pulse correlates with both the duration of the first pulse and the interpulse separation, indicating that there is memory within the burst of the energy released from the first pulse. If the pulse emission timescale indicates the kinematics of relativistically jetted material, then these correlations suggest energy loss as the jet moves outward. We have shown that these results are redshift independent and therefore intrinsic, as expected from models involving external shocks. However, this interpretation is inconsistent with results obtained previously for long GRBs (Ramirez-Ruiz & Fenimore 2000), as long GRBs do not show...
either increasing interpulse separations or increasing pulse durations.

The original basis for the short GRB class was BATSE’s duration bimodality (Kouveliotou et al. 1993): this discovery led to the idea that the short GRB emission timescale necessitated compact merger models rather than those involving hyper- and supernovae. Afterglows, host galaxies, and a wide range of evidence provided from nonprompt emission support the idea that short and long/intermediate GRBs originate in different environments, produced by different hosts. The recent discovery of a gravitational wave “chirp” associated with short (or possibly intermediate) GRB 170817A (The LIGO Scientific Collaboration et al. 2017) is consistent with the neutron star–neutron star merger model of short GRBs.

Most theoretical models explain GRB emission as originating from emitting regions located far from the progenitor. These models assume that the progenitors contribute indirectly to the pulse properties via the amount of material they eject, the relativistic velocity of this ejected material, and the angular characteristics of the beamed jets produced. The physics of pulsed GRB emission can thus be similar for different GRB classes even if their progenitors are very different. Jet models involve relativistic material moving away from the progenitor and toward the observer at extremely high velocities (Lorentz factor \(100 \leq \Gamma \leq 1000\)); these can lead to significantly time-compressed durations \((w_{\text{observed}} = w/(1 + \Gamma^2))\) for any emission that is produced in the jet frame. Such extreme time compression should produce pulses too short to be consistent with observed pulse durations. For example, the duration of GRB 170817A’s pulsed emission is too long to have undergone time compression of order \(10^4\); thus, the emission could not have been created in the frame of the expanding shell. One solution to this problem is to have the emitting region relatively stationary with respect to the observer. In other words, the pulsed emission needs to be produced in a stationary external medium rather than internal to the expanding jet. Furthermore, the burst duration must reflect the activity time of the central engine rather than episodic emission from within the moving jet, because if it did, time compression would smear out the duration bimodality and observed class boundaries.

The similarities between pulse properties observed across GRB classes suggests that the prompt emission in long, short, and intermediate bursts alike originates from a similar physical mechanism, even if multipulsed long/intermediate GRBs do not exhibit pulse lengthening associated with external shocks. This inconsistency might be resolved if short GRB pulses represent sequential episodes, moving outward from a single event, while long/intermediate GRB pulses are independent (unlinked) episodes, corresponding to different events occurring within the line of sight. Despite their many similarities, short-duration and long-/intermediate-duration GRBs exhibit several different prompt emission characteristics that can be used to help classify them:

1. More short GRBs appear to be single-pulsed (90%) than long/intermediate GRBs (25%–40%).
2. Multipulsed short GRBs exhibit correlated pulse durations and interpulse separations, whereas multipulsed long/intermediate GRBs do not.
3. Durations of short GRB pulses are shorter than those of long/intermediate GRB pulses.
4. Short GRB pulses are spectrally harder than long/intermediate GRB pulses and undergo greater hard-to-soft evolution.
5. The light curves of short GRBs generally exhibit more pronounced precursor and decay peaks than long/intermediate GRB pulses.

Finally, our catalog development approach has led to the discovery of a new type of gamma-ray transient. Crescendo GRBs have longer rise times than decay times and cannot be adequately modeled by asymmetry in the Norris et al. (2005) pulse model. Some crescendo GRBs are characterized by a series of rapid-fire staccato pulses leading up to the crescendo, while others have a crescendo that is preceded by a complex pulse that may be composed of unresolved staccato pulses or may be composed of a complex emission episode that is similar to the extended emission found in some short GRBs. Crescendo GRBs might be a subset of GRBs (representing, for example, neutron star–black hole mergers), but they might also represent a completely different type of gamma-ray transient. We have found at least one example of what appears to be a long crescendo GRB, suggesting that crescendo characteristics, like triple-peaked pulse structures, do not belong only in the realm of long- or short-duration GRB classification.

We have demonstrated that the prompt pulses from short GRBs share much in common with pulses from long/intermediate GRBs, even as they exhibit important differences. The authors hope that this BATSE TTE GRB pulse catalog helps invite new patterns of inquiry on short GRBs, as well as on potential common emission mechanisms.

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References

Bagoly, Z., Mészáros, A., Horváth, I., Balázs, L. G., & Mészáros, P. 1998, ApJ, 498, 342
Balaschegui, A., Ruiz-Lapuente, P., & Canal, R. 2001, MNRAS, 328, 283
Balázs, L. G., Bagoly, Z., Horváth, I., Mészáros, A., & Mészáros, P. 2003, A&A, 401, 129
Berger, E. 2014, ARA&A, 52, 43
Blanchard, P. K., Berger, E., & Fong, W.-F. 2016, ApJ, 817, 144
Borgonovo, L. 2004, A&A, 418, 487
Bostanci, Z. F., Kaneko, Y., & Göğüş, E. 2013, MNRAS, 428, 1623
Campana, S., Manganaro, V., Blustin, A. J., et al. 2006, Nature, 442, 1008
Chattopadhyay, S., & Maitra, R. 2017, MNRAS, 469, 3374
Chattopadhyay, T., Misra, R., Chattopadhyay, A. K., & Naskar, M. 2007, ApJ, 667, 1017
de Ugarte Postigo, A., Horváth, I., Veres, P., et al. 2011, A&A, 525, A109
Dichiara, S., Guidorzi, C., Frontera, F., & Amati, L. 2013, ApJ, 777, 132
Fishman, G. J. 2013, in EAS Publications Ser. 61, Gamma-ray Bursts: 15 Years of GRB Afterglows — Progenitors, Environments and Host Galaxies from the Nearby to the Early Universe, ed. A.J. Castro-Tirado, J. Gorosabel, & I. H. Park (Málagia: EAS)
Frail, D. A., Kulkarni, S. R., Sari, R., et al. 2001, ApJL, 562, L55
Frank, E., Hall, M. A., & Wittan, I. H. 2016, The WEKA Workbench. Online Appendix for “Data Mining: Practical Machine Learning Tools and Techniques” (4th ed.; San Mateo, CA: Morgan Kaufmann Publishers)
Goldstein, A., Preece, R. D., Mollozzi, R. S., et al. 2013, ApJS, 208, 21
