A Further Study of the $t_{\text{Burst}}$ of GRBs: Rest-frame Properties, External Plateau Contributions, and Multiple Parameter Analysis

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Abstract

Zhang et al. propose to redefine the true $\gamma$-ray burst (GRB) central engine activity duration, $t_{\text{Burst}}$, by considering the contributions from the prompt $\gamma$-ray emission, X-ray flare, and internal plateau features. With a comprehensive study of a large sample of Swift GRBs, it is shown that the $t_{\text{Burst}}$ distribution in the observer frame consists of a bimodal feature, suggesting the existence of a new population of ultra-long GRBs. In this work, we make a series of further studies on $t_{\text{Burst}}$; we update the Swift GRB sample up to 2016 June; we investigate the properties of $t_{\text{Burst}}$ distribution in the rest frame; we redefine $t_{\text{Burst}}$ by involving external plateau contributions; and we make a multiple parameter analysis to investigate whether the bursts within the ultra-long population are statistically different in the sense of other features besides the duration distribution. We find that for all situations, the distribution of $t_{\text{Burst}}$ requires two normal distributions in logarithmic space to provide a good fit both in the observer frame and in the rest frame. Considering the observational gap effect would not completely erase the bimodal distribution feature. However, the bursts within the ultra-long population may have no statistical difference in the sense of other features besides the duration term. We thus suggest that if the ultra-long population of GRBs indeed exists, their central engine and radiation mechanisms should be similar to those of the normal population, but they have a longer central engine activity timescale.

Key words: gamma-ray burst: general

1. Introduction

Gamma-ray bursts (GRBs) are the most extreme explosive events in the universe (see Kumar & Zhang 2015 for a recent review). Based on their temporal and spectral statistical properties, GRBs were classified into two categories: the long-duration, soft-spectrum class (LGRBs) and the short-duration, hard-spectrum class (SGRBs; Kouveliotou et al. 1993). After decades of observations, it turns out that such a phenomenological classification indeed implies different natures, e.g., different types of progenitors were invoked for these two different classes. The SGRBs are connected with mergers of two compact stellar objects (NS–NS and NS–BH systems; Paczyński 1986; Eichler et al. 1989; Paczyński 1991; Narayan et al. 1992), and the LGRBs are connected with core collapse from Wolf–Rayet stars (Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999; Woosley & Bloom 2006).

Typically, the prompt duration of LGRBs is tens of seconds. However, there is a subclass of LGRBs (e.g., GRBs 101225A, 111209A, 121027A, and 130925A) showing unusually long prompt durations, as long as hours (Gendre et al. 2013; Stratta et al. 2013; Virgili et al. 2013; Levan et al. 2014; Greiner et al. 2015). In these references, GRBs with $\gamma$-ray duration $T_90$ comparable to or larger than $10^3$ s were defined as “ultra-long GRBs (ulGRBs).” Some authors proposed that these ulGRBs may belong to a new population (Gendre et al. 2013; Nakauchi et al. 2013; Levan et al. 2014; Greiner et al. 2015; Ioka et al. 2016), and they may issue from a new type of progenitor, such as blue supergiants (Mészáros & Rees 2001; Nakauchi et al. 2013) or dwarf tidal disruption events (Ioka et al. 2016), or they may have a special central engine, such as a strongly magnetized millisecond neutron star (magnetar; Levan et al. 2014; Greiner et al. 2015).

Virgili et al. (2013) investigated the $\gamma$-ray duration distribution of LGRBs, and they claimed that the overall distribution is consistent with a log-normal distribution: namely, ulGRBs are the tail of the distribution of normal LGRBs, rather than corresponding to a new possible population.

However, many Swift GRBs show interesting features in their X-ray light curves, such as flares (Burrows et al. 2005; Zhang et al. 2006; Margutti et al. 2011) and shallow decay plateaus (Liang et al. 2007; Troja et al. 2007), signifying an extended central engine activity time. Thus, it has been widely argued that the prompt duration may not be able to reflect the intrinsic central engine activity. Some authors propose to redefine the burst duration (e.g., $t_{\text{Burst}}$) by taking into account both $\gamma$-ray and the aforementioned X-ray light-curve features (Zhang et al. 2014; Boër et al. 2015). Such a definition is not easy to quantify, since late-time X-ray features need not necessarily be related to late central engine activity. The observed (E$\gamma$-ray and X-ray) flux is contributed by both internal dissipation emission (e.g., internal shocks or magnetic dissipation) and the afterglow emission from the external shock. The prompt $\gamma$-ray emission, X-ray flares, and so-called “internal X-ray plateau” (a plateau in the light curve followed by a very rapid decay) likely originate from internal dissipation, which essentially reflects the intrinsic central engine activity (Nousek et al. 2006; Zhang et al. 2006). However, the so-called “external X-ray plateau” (a plateau in the light curve followed...
by a normal decay as expected from the external shock model) likely originates from external shock emission, and the plateau phase might be due to the late central engine energy injection, but it could also be due to internal collisions or refreshed external collisions from early ejected shells (Rees & Mészáros 1998; Sari & Mészáros 2000; Gao et al. 2013). For the latter case, the external plateau phase no longer reflects the intrinsic central engine activity.

For a secure lower limit, $T_{\text{burst}}$ could be defined by the last steep-to-shallow transition in the observed ($\gamma$-ray and X-ray) flux, which essentially incorporates the prompt $\gamma$-ray emission, X-ray flares, and internal plateau phase (Zhang et al. 2014; Boër et al. 2015). With a comprehensive study on a large sample of Swift GRBs, it is shown that the engine activity time is frequently much larger than $T_{90}$ (Zhang et al. 2014). Even if the $T_{90}$ distribution could be well fit by a log-normal distribution, the $T_{\text{burst}}$ distribution consists of a much larger tail that requires an additional component to provide a good fit (Zhang et al. 2014; Boër et al. 2015). However, due to the low significance, Zhang et al. (2014) and Boër et al. (2015) had different opinions on the interpretation of this tail, with Zhang et al. (2014) suggesting that the bimodal distribution of $T_{\text{burst}}$ may be strongly affected by some selection effects so that an ultra-long population cannot be confirmed, while Boër et al. (2015) inferred that the ultra-long population is statistically different.

Recently, within the framework of the internal-external shock model, Gao & Mészáros (2015) developed a numerical code to study the relationship between $T_{90}$ and $T_{\text{burst}}$, as well as the intrinsic central engine activity timescale $T_{\text{ce}}$. They found that the values of $T_{90}$ and $T_{\text{burst}}$ could be larger than $T_{\text{ce}}$ due to internal collisions or refreshed external collisions from early ejected shells, but this is only valid when $T_{\text{ce}} \gtrsim 10^4$ s. In other words, “external X-ray plateau” could also reflect the intrinsic central engine activity as long as $T_{\text{ce}} \gtrsim 10^4$ s.

In this work, we systematically investigate Swift GRBs from the launch of Swift to 2016 June. We attempt to answer the following interesting questions. (1) Both Zhang et al. (2014) and Boër et al. (2015) focused on the duration distribution in the observed frame. Does the conclusion become different when considering the duration distribution in the rest frame? (2) Does the distribution tail of $T_{\text{burst}}$ become more significant when the external X-ray plateau is invoked? (3) If the bimodal distribution of $T_{\text{burst}}$ indeed exists, are the bursts within the ultra-long population statistically different in the sense of other features besides the duration distribution; for instance, do these two populations show distinct separation in the multiple-parameter analysis, such as in the $E_{p,z} - E_{\gamma,\text{iso}}$ and $E_{p,z} - L_{\gamma,\text{iso}}$ diagrams?

## 2. Data Analysis

Between 2005 January and 2016 June, 1032 Swift GRBs were detected by Swift/XRT, with 728 GRBs having well-sampled X-ray telescope (XRT) light curves, namely, the X-ray light curve contains at least six data points, excluding upper limits. In order to measure $T_{\text{burst}}$, we download the XRT light curves from the Swift/XRT team website (Evans et al. 2009) at the UK Swift Science Data Centre (UKSSDC) that were processed with HEASOFT version 6.12. We then apply a multivariate adaptive regression splines (MARS) technique (e.g., Friedman 1991) to the observed light curves in the logarithmic (log) scale. MARS is a nonparametric regression technique that could automatically determine both variable selection and functional form, resulting in an explanatory predictive model. Such a MARS model can be expressed as a linear combination of piecewise polynomial basis functions (including constant and the so-called Hinge functions) that are joined together smoothly at the knots. When using MARS for modeling the relationship between the predictor and dependent variables, it is not necessary to know the functional forms of the relationships; MARS establishes them based on the data (see Osei-Bryson & Ngwenyama 2014 for a detailed overview of MARS techniques). Applied to Swift/XRT data, MARS could automatically fit the light curves with multi-segment broken power-law functions, detect and optimize all breaks, and record the power-law indices for each segment. The results of such a technique are consistent with the automated light-curve fitting results provided by the XRT GRB online catalog (see the Appendix for more details). Nevertheless, such a technique could also incorporate the steep decay and flare phases, which are essential to measure $T_{\text{burst}}$ (Zhang et al. 2014).

We then distribute 728 bursts into four categories:

1. **Bursts in the first three categories do not consist of X-ray flares:** (1) 308 bursts with either simple power-law decay light curves or broken power-law decay light curves but without showing any steep decay\(^9\) (power-law index steeper than $-3$) or plateau signature\(^10\) (defined as a temporal segment with a decay slope $\leq 0.6$); (2) 40 bursts with steep decay features but without showing any flare or plateau features; and (3) 145 bursts without flare features but consisting of plateau features in the light curve. Finally, 235 bursts consisting of X-ray flare features are distributed into the fourth category.

2. **For the first category (e.g., 308 GRBs),** we collect their $\gamma$-ray duration $T_{90}$, redshift $z$ (if available), and spectral parameters such as the peak energy in the energy spectrum $E_p$, spectral index of power-law fitting $\Gamma$, isotropic $\gamma$-ray energy $E_{\gamma,\text{iso}}$, and peak luminosity $L_{\gamma,\text{iso}}$. Please refer to Li et al. (2016) for details of data collecting and the definition and calculation of the spectral parameters.

3. **For the second category (e.g., 40 GRBs),** we record the transition time of steep decay to normal decay (defined as a temporal segment with decay slope $0.6 < \alpha < 3$) as $t_{\text{dp}}$.

   Within the third category (e.g., 145 GRBs), 10 bursts consist of internal plateaus, and 135 bursts consist of external plateaus. For the internal plateau sample, the plateau is followed by a steep decay segment. We record the end of this steep decay phase as $t_{\text{dp}}$. For the external plateau sample, we record the last plateau to normal decay transition time as the ending time of the plateau, $t_{\text{fpa}}$. Note that among the external plateau sample, we have 62 GRBs with $t_{\text{fpa}} \gtrsim 10^4$ s and 73 GRBs with $t_{\text{fpa}} < 10^4$ s.

   Within the fourth category (e.g., 235 GRBs), 50 GRBs show additional plateau features after the last X-ray flare, with three

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9. For steep decay, the steepest decay slope in an external shock model is $2 + \beta$ (Kumar & Panaitescu 2000), which is typically smaller than 3 and is defined by the high-latitude “curvature effect” emission from a conical outflow, even if the emission abruptly ceases.

10. For the plateau phase, there is no stringent definition on its decay slope. However, according to the standard external shock model (see Gao et al. 2013 for a review), a natural interpretation of the plateau phase is to attribute it to a continuous energy injection, so that the forward shock is “refreshed.” The energy injection process could be effectively interpreted as the central engine itself being longer lasting, with a power-law luminosity history $L \propto t^{-\gamma}$. The effective $\gamma$ value inferred from the observations is around 0.5 (Zhang et al. 2006). Adopting $\gamma = 0.5$ and assuming the electron spectral index $p = 2.2$, we have the plateau decay index as $-\gamma \lesssim 0.6$, which is taken as the criteria of the plateau decay slope.
being internal plateaus and 47 being external plateaus. For all 235 bursts, we record the end of the last steep decay phase as \( t_{\text{stp}} \). For the 185 GRBs without plateaus, \( t_{\text{stp}} \) corresponds to the ending time of the last flare. For the three bursts with internal plateaus, \( t_{\text{stp}} \) corresponds to the ending time of the last steep decay phase following the plateau. For the 47 bursts showing external plateaus, we record the last plateau to normal decay transition time as the ending time of the plateau, \( t_{\text{pla}} \).

For all GRBs in categories 2–4, we also collect their \( \gamma \)-ray duration \( T_{90} \), redshift \( z \) (if available), and spectral parameters similar to category 1. Note that in the appendix (Figure 5), we show some examples of our fitting results for different types of light curves, with marks of \( t_{\text{stp}} \) and \( t_{\text{pla}} \) (if applicable), to better illustrate the light-curve properties for each of the four categories.

### 3. Results

In Zhang et al. (2014), the burst duration \( t_{\text{burst}} \) is defined as the maximum of \( T_{90} \) of \( \gamma \)-ray emission and the transition time of the last steep-to-shallow transitions in the X-ray light curve. In this case, for our category 1, \( t_{\text{burst}} \) equals \( T_{90} \). For our categories 2, 3, and 4, we have \( t_{\text{burst}} = \max (t_{\text{stp}}, T_{90}) \). We plot the distribution of \( t_{\text{burst}} \) in log space in Figure 1(a). We perform the Lilliefors test (i.e., the Kolmogorov–Smirnov test for normality with mean and variance unknown; Lilliefors 1967, 1969) on this distribution, and it rejects the null hypothesis of normality at the \(<0.001 \) significance level. We thus fit the distribution with a mixture of two normal distributions in log space and with \( \chi^2 \) test statistics to find the best-fit parameters. In this case, we fit the distribution with a mixture of two normal distributions with a narrow, significant peak at 173.8 s and a wider, less significant peak at 2.75 \( \times \) 10\(^4\) s, respectively. The division line between the two normal distributions is \( t_{\text{burst}} = 1.86 \times 10^4 \) s. In the last column of Table 1 (Adjusted \( R^2 \)), we show the determine coefficient of the best fit.

In our sample, there are 338 GRBs with redshift measurements. For these bursts, the distribution of \( t_{\text{burst}} \) in the rest frame is shown in Figure 1(b). According to the Lilliefors test, the distribution rejects the null hypothesis of normality at the \(<0.001 \) significance level. The distribution can be fitted with a mixture of two normal distributions in log space, with one peak at 79.4 s and the other peak at 1.66 \( \times \) 10\(^4\) s. The division line between the two normal distributions is \( t_{\text{burst}}(1 + z) = 6.76 \times 10^3 \) s.

As discussed in Zhang et al. (2014), this apparent bimodal distribution might be subject to selection effects due to observational biases, especially the observational gap effect. In general, for XRT GRB observations, there is an observational gap around thousands of seconds due to reasons such as the geometry configuration between the satellite orbital position relative to the GRB source position, instrumental feature of the satellite, and delay of observation in respect to the priority of other ongoing observations. All these factors act as a selection effect against finding \( t_{\text{burst}} \) values within this gap, which may explain the sudden drop of \( t_{\text{burst}} \) around \(~1000 \) s. To justify such a selection effect, we systemically go through our entire sample. We find that for 80% of the bursts, the XRT data before the observational gap could be fitted with a single power-law decay, and the power-law fitting could be well extrapolated to the observational data after the gap. For 10% of the bursts, the XRT data before the observational gap could be fitted with a single power-law decay, while the gap together with the data after the gap could be fitted with another single power-law decay. Nevertheless, the starting point of the gap is far away from the last flare. For 90% of the sources, it should be a small probability to have \( t_{\text{burst}} \) falling in the observational gap. For the other 10% of the bursts, there appears to be X-ray flares before the observational gap, and the ending time of the last flare is very close to the beginning time of the gap. For these sources, it is possible that some later X-ray flares are missed due to the data gap, and \( t_{\text{burst}} \) indeed falls into the gap region. For these bursts, we record the ending time of their observational gap as \( t_{\text{gap}} \).

For testing the selection effect, we recalculate the \( t_{\text{burst}} \) value for these sources as \( t_{\text{burst}} = \max (t_{\text{stp}}, T_{90}, t_{\text{gap}}) \). We plot the new distribution of \( t_{\text{burst}} \) and \( t_{\text{burst}}(1 + z) \) in Figures 1(c) and (d). The Lilliefors test result rejects the null hypothesis of normality of the distribution of \( t_{\text{burst}} \) at \(<0.001 \) significance level and the null hypothesis of normality of the distribution of \( t_{\text{burst}}(1 + z) \) at the 0.004 significance level. The distribution of \( t_{\text{burst}} \) could be fitted with a mixture of two normal distributions in log space, with one peak at 158.5 s and the other peak at 2.09 \( \times \) 10\(^4\) s. The division line between the two normal distributions is \( t_{\text{burst}}(1 + z) = 3.46 \times 10^3 \) s. It turns out that the bimodal distribution feature of \( t_{\text{burst}} \) and \( t_{\text{burst}}(1 + z) \) is not due to the selection effect. We thus propose that in terms of burst duration \( t_{\text{burst}} \) or \( t_{\text{burst}}(1 + z) \) (i.e., the central engine activity timescale in either the observer frame or the rest frame), a new population of ultra-long GRBs indeed exists.

It is of great interest to investigate whether the bursts within the ultra-long population are statistically different in the sense of other features besides the duration distribution. We thus plot our collected prompt emission parameters, such as \( E_p \), \( \Gamma \), \( E_{\text{v,iso}} \), and \( L_{\gamma,\text{iso}} \) in pairs in 2D distribution diagrams (see Figure 2). We find that, except for the duration distribution, there are no distinct 2D distribution plots that can clearly separate the ultra-long population of GRBs from the normal population.

In case of possible selection biases from Li et al. (2016), which compiles all possible data from various sources, we also compare the properties of our ultra-long population with a Swift-only sample. In the Swift-only sample, properties such as \( E_p \), \( \Gamma \), fluency, and peak flux are obtained from the Swift/GRB table,\(^{11} \) and \( E_{\text{v,iso}} \) and \( L_{\gamma,\text{iso}} \) are estimated with Swift-based properties. We examine the same 2D plots with these Swift-based properties and obtain a consistent result with what we show in Figure 2; i.e., the ultra-long population cannot be distinguished from these 2D diagrams. Such a conclusion is applicable to all situations discussed in the following.

According to Gao & Mészáros (2015), as long as the ending time is large enough (e.g., \( \geq 10^4 \) s), external X-ray plateaus could also reflect the intrinsic central engine activity. In this work, we suggest redefining the burst duration \( t_{\text{burst}} \) by including the contribution from such late external X-ray plateaus. Specifically, for our category 1, \( t_{\text{burst}} \) equals \( T_{90} \). For our categories 2 and 4, we have \( t_{\text{burst}} = \max (t_{\text{stp}}, T_{90}) \). Within our category 3, for the 62 GRBs with external plateaus and \( t_{\text{pla}} \geq 10^4 \) s, we have \( t_{\text{burst}} = t_{\text{pla}} \). For the other 83 GRBs within category 3, we have \( t_{\text{burst}} = \max (t_{\text{stp}}, T_{90}) \). In this case, we plot the distribution of

\(^{11} \) http://swift.gsfc.nasa.gov/archive/grb_table/
According to the Lilliefors test, the distribution rejects the null hypothesis of normality at the \( \leq 0.001 \) significance level. The distribution can be fitted with a mixture of two normal distributions in log space, with one peaking at 166.0 s and the other peaking at \( 3.02 \times 10^4 \) s. The division line between the two normal distributions is \( t_{\text{burst}} = 1.02 \times 10^4 \) s. In this case, the distribution of \( t_{\text{burst}} \) in the rest frame is shown in Figure 1(f). According to the Lilliefors test, the distribution rejects the null hypothesis of normality at the \( \leq 0.001 \) significance level. The distribution can be fitted with a mixture of two normal distributions in log space, with one peaking at 81.3 s and the other peaking at \( 1.29 \times 10^4 \) s.

The division line between the two normal distributions is \( t_{\text{burst}}/(1 + z) = 4.17 \times 10^3 \) s. Considering the observational gap effect, the distributions of \( t_{\text{burst}} \) and \( t_{\text{burst}}/(1 + z) \) are shown in Figures 1(g) and (h). The Lilliefors test result rejects the null hypothesis of normality of the distribution of \( t_{\text{burst}} \) at the \( \leq 0.001 \) significance level and the null hypothesis of normality of the distribution of \( t_{\text{burst}}/(1 + z) \) at the 0.002 significance level. The distribution of \( t_{\text{burst}} \) could be fitted with a mixture of two normal distributions in log space, with one peaking at 147.9 s and the other peaking at \( 2.04 \times 10^4 \) s. The division line between the two normal distributions is \( t_{\text{burst}} = 5.37 \times 10^3 \) s. The distribution of \( t_{\text{burst}}/(1 + z) \) could be
fitted with a mixture of two normal distributions in log space, with one peaking at 64.6 s and the other peaking at 5.37 × 10^3 s. The division line between the two normal distributions is t_{burst}/(1 + z) = 1.66 × 10^3 s.

In principle, even if the ending time is not larger than 10^4 s, the external X-ray plateau could also be due to the late central engine energy injection. If so, within our category 3, for all GRBs with external plateaus, we should have t_{burst} = t_{fla}. In this case, we plot the distribution of t_{burst} in log space in Figure 1(i). According to the Lilliefors test, the distribution rejects the null hypothesis of normality at the 0.002 significance level. The distribution can be fitted with a mixture of two normal distributions in log space, with one peaking at 229.1 s and the other peaking at 2.09 × 10^4 s. The division line between the two normal distributions is t_{burst} = 9.33 × 10^3 s. For the sample with a redshift measurement, the distribution of t_{burst} in the rest frame is shown in Figure 1(j). According to the Lilliefors test, the distribution rejects the null hypothesis of normality at the ≤ 0.001 s significance level. The distribution can be fitted with a mixture of two normal distributions in log space, with one peaking at 123.0 s and the other peaking at 1.66 × 10^4 s. The division line between the two normal distributions is t_{burst}/(1 + z) = 5.89 × 10^3 s. Considering the observational gap effect, the distributions of t_{burst} and t_{burst}/(1 + z) are shown in Figures 1(k) and (l). The Lilliefors test result rejects the null hypothesis of normality of the distribution of t_{burst} at the ≤ 0.001 significance level. The distribution of t_{burst} could be fitted with a mixture of two normal distributions in log space, with one peaking at 218.8 s and the other peaking at 1.51 × 10^4 s. The division line between the two normal distributions is t_{burst} = 6.31 × 10^3 s.

It is worth noting that in this case, the distribution of t_{burst}/(1 + z) could accept the null hypothesis of normality at the 0.274 significance level. The distribution of t_{burst}/(1 + z) could be fitted with a single normal distribution in log space, peaking at 245.5 s. Such a result implies that if all external X-ray plateaus are generated by the late central engine energy injection, and if t_{burst} indeed falls into the observational gap region for some GRBs (e.g., GRBs containing X-ray flares before the observational gap and the ending time of the last flare is very close to the beginning time of the gap), the bimodal distribution of t_{burst} does not exist; namely, ultra-long GRBs are the tail of the distribution of normal LGRBs rather than corresponding to a new possible population, which would be consistent with the fact that no distinct 2D distribution plots could clearly separate the ultra-long population of GRBs from the normal population.

In our category 4, 50 bursts also contain external plateaus at late times. However, the external plateaus in these cases could be naturally explained without invoking late central engine activity, since for GRBs with X-ray flares, it is believed that the late ejecta that causes the flares would continue to overtake and refresh the afterglow shock, thus causing additional activity at even later times in the light curve. Although the possibility is low, for completeness, we also test the situation of these external plateaus reflecting central engine activity. In this case, for category 4, we have t_{burst} = max (t_{slp}, t_{obs}, t_{fla}). We plot the new distribution of t_{burst} in log space in Figure 1(m). According to the Lilliefors test, the distribution rejects the null hypothesis of normality at the ≤ 0.001 significance level. The distribution can be fitted with a mixture of two normal distributions in log space, with one peaking at 190.5 s and the other peaking at 2.00 × 10^4 s. The division line between the two normal distributions is t_{burst} = 6.76 × 10^3 s. For the sample with a redshift measurement, the distribution of t_{burst} in the rest frame is shown in Figure 1(n). According to the Lilliefors test, the distribution rejects the null hypothesis of normality at the 0.009 significance level. The distribution can
be fitted with a mixture of two normal distributions in log space, with one peaking at 102.3 s and the other peaking at 8.71 × 10^3 s. The division line between the two normal distributions is \( t_{\text{burst}}/(1 + z) = 2.34 \times 10^3 \text{s} \). Considering the observational gap effect, the distributions of \( t_{\text{burst}} \) and \( t_{\text{burst}}/(1 + z) \) are shown in Figures 1(o) and (p). The Lilliefors test result rejects the null hypothesis of normality of the distribution of \( t_{\text{burst}} \) at the ≤0.001 significance level and the null hypothesis of normality of the distribution of \( t_{\text{burst}}/(1 + z) \) at the 0.046 significance level. The distribution of \( t_{\text{burst}} \) could be fitted with a mixture of two normal distributions in log space, with one peaking at 158.5 s and the other peaking at 1.91 × 10^4 s. The division line between the two normal distributions is \( t_{\text{burst}} = 5.50 \times 10^3 \text{s} \). The distribution of \( t_{\text{burst}}/(1 + z) \) could be fitted with a mixture of two normal distributions in log space, with one peaking at 109.6 s and the other peaking at 1.17 × 10^4 s. The division line between the two normal distributions is \( t_{\text{burst}}/(1 + z) = 2.34 \times 10^3 \text{s} \). Note that for the 50 GRBs containing external plateaus, 36 are with \( t_{\text{pla}} \gtrsim 10^4 \text{s} \) and 14 are with \( t_{\text{pla}} < 10^4 \text{s} \). For the 14 bursts, most of their \( t_{\text{pla}} \) values are only slightly smaller than \( 10^4 \text{s} \), so separating out these bursts did not make too much difference for the results. That is why we did not present the results by separating the 50 bursts as we did in category 3.

4. Conclusion and Discussion

It has been widely discussed that the true GRB central engine activity duration, \( t_{\text{burst}} \), should be defined by considering both \( \gamma \)-ray and X-ray data. In principle, the prompt \( \gamma \)-ray emission, X-ray flares, internal X-ray plateau, and even external X-ray plateau could all have originated from internal dissipation, which essentially reflects the intrinsic central engine activity. In this work, we systematically investigated 1032 Swift GRBs that were detected by XRT from 2005 January to 2016 June, and we did the following investigations. Following Zhang et al. (2014), the definition of \( t_{\text{burst}} \) would be the maximum of the \( T_{\text{90}} \) of \( \gamma \)-ray emission and the transition time of the last steep-to-shallow transitions in the light curve. To investigate whether the bursts within the ultra-long population are statistically different in the sense of other features besides the duration distribution, we plot the prompt emission parameters, such as \( E_{\text{p}}, \Gamma, E_{\gamma, \text{iso}} \), and \( L_{\gamma, \text{iso}} \), in pairs in 2D distribution diagrams and find that, except for the duration distribution, there are no distinct 2D distribution plots that can clearly separate the ultra-long population of GRBs from the normal population.

In contrast, we suggest redefining the burst duration \( t_{\text{burst}} \) by including the contributions from the external X-ray plateaus. Among our sample, there are 135 bursts consisting of external plateaus but without X-ray flares and 47 bursts showing X-ray flares and additional external plateau features after all flares. For the external plateau sample, we have 62 GRBs with
$t_{\text{pla}} \gtrsim 10^4 \text{ s}$ and 73 GRBs with $t_{\text{pla}} < 10^4 \text{ s}$. According to Gao & Mészáros (2015), as long as the ending time is large enough (e.g., $\gtrsim 10^4 \text{ s}$), external X-ray plateaus could surely reflect the intrinsic central engine activity. However, for external plateaus whose ending time is relatively small (e.g., $< 10^4 \text{ s}$), the plateau phase might be due to the late central engine energy injection, but it also could be due to the internal collisions or refreshed external collisions from early ejected shells, whereas the external plateau phase no longer reflects the intrinsic central engine activity. For the 47 bursts showing X-ray flares and additional external plateaus, the possibility is even lower that the external plateaus reflect central engine activity, since for GRBs with X-ray flares, it is believed that the late ejecta that causes the flares would continue to overtake and refresh the afterglow shock, thus causing additional activity at even later times in the light curve.

In this work, we first only involve the contributions from the late external plateaus (e.g., $\gtrsim 10^4 \text{ s}$). We find that the bimodal distribution feature of $t_{\text{burst}}$ and $t_{\text{burst}}/(1 + z)$ becomes more significant, and the bimodal feature does not disappear when the observational gap effect is considered. Second, for all GRBs without X-ray flares but with external plateaus, we involve the contributions from the external plateaus. We find that the bimodal distribution feature of $t_{\text{burst}}$ and $t_{\text{burst}}/(1 + z)$ still exists, but the distribution of $t_{\text{burst}}/(1 + z)$ could accept the null hypothesis of normality (i.e., could be fitted with a single normal distribution in log space) at the 0.274 significance level when the observational gap effect is considered. Finally, for GRBs with both X-ray flares and external plateaus, we also involve the contributions from the external plateaus. We find that the bimodal distribution feature of $t_{\text{burst}}$ and $t_{\text{burst}}/(1 + z)$ always exists, even when the observational gap effect is considered.

Based on the results of our investigations, the following physical implications could be inferred.

For all situations, the distribution of the $t_{\text{burst}}$ of GRBs requires two normal distributions in log space to provide a good fit, both in the observer frame and the rest frame. Considering the observational gap effect would not completely erase the bimodal distribution feature. The bimodal feature may suggest that an ultra-long population indeed exists, at least in regard to duration. However, no distinct 2D distribution plots of prompt parameters could clearly separate the ultra-long population of GRBs from the normal population, meaning that the bursts within the ultra-long population may have no statistical difference in the sense of other features besides the duration term. To reconcile these two results, we suggest that if the ultra-long population of GRBs indeed exists, their central engine and radiation mechanisms should be similar to those of the normal population, but they somehow have a longer central engine activity timescale. Under the framework of the collapsar model, the central engine (black hole) activity timescale could have a wide range, depending not only on the size of the progenitor star but also on the stellar structure and rotation rate of the progenitor star (Kumar et al. 2008a, 2008b). Invoking a larger size of progenitor star, such as a blue supergiant-like progenitor for ultra-long GRBs, could naturally explain the unusually long duration. However, Greiner et al. (2015) recently reported the first discovered association between an ultra-long GRB and a supernova, i.e., GRB 111209A/SN 2011kl. Based on the observed properties of SN 2011kl, such as its spectra and light-curve shape, they ruled out a blue supergiant progenitor interpretation for GRB 111209A.

Alternatively, a collapsar model with fallback accretion has been proposed to interpret the ultra-long population of GRBs and has been successfully applied to fit the broadband data of some typical ultra-long GRBs, such as GRB 121027A (Wu et al. 2013) and GRB 111209A/SN 2011kl (Gao et al. 2016). In general, the size of the progenitor star for the two populations might be similar, but the stellar structure and rotation rate of the progenitor star may be different. The stellar structure and rotation rate could affect the fallback process of the envelope material, which could largely extend the central engine activity time, allowing a chance to give rise to the ultra-long GRBs. In contrast, the bounding shock responsible for the associated SN and the baryon-rich wide wind/outflow through the Blandford–Payne (Blandford & Payne 1982) mechanism from the initial accretion disk would transfer kinetic energy to the envelope materials. If the injected kinetic energy is less than the potential energy of the envelope material, the starting time of the fallback will be delayed, which may even prolong the burst duration. However, if the injected kinetic energy is larger, which might be the majority of cases, the fallback process vanishes and the central engine activity is relatively short, corresponding to the normal LGRBs (Gao et al. 2016).

Note that for one situation—namely, that assuming all external X-ray plateaus are generated by the late central engine energy injection (but not involving the external plateau after flares) and if $t_{\text{burst}}$ indeed falls into the observational gap region for some GRBs (e.g., GRBs containing X-ray flares before the observational gap and the ending time of the last flare is very close to the beginning time of the gap)—the bimodal feature of $t_{\text{burst}}$ could be erased by the observational gap effect. It is still possible that ultra-long GRBs are the tail of the distribution of normal LGRBs rather than corresponding to a new possible population, which would be consistent with the fact that no distinct 2D distribution plots could clearly separate the ultra-long population of GRBs from the normal population.

Finally, it is worth noticing that besides the observational gap effect, there are some other selection effects that might affect the determination of $t_{\text{burst}}$, such as the sensitivity of XRT and the observation ceasing in respect to the priority of other ongoing observations (other GRBs or target of opportunities). These effects could cause underestimation of $t_{\text{burst}}$. Since the XRT observation ending time for $\geq 90\%$ of the GRBs in our sample is larger than $10^4 \text{ s}$, the underestimation of $t_{\text{burst}}$ could only make the ultra-long population even more significant and the bimodal distribution of $t_{\text{burst}}$ more clear.

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Appendix

The MARS technique (Friedman 1991) is a nonparametric regression technique that could automatically determine both variable selection and functional form, resulting in an explanatory predictive model. Such a MARS model is a linear combination of piecewise polynomial basis functions and can be expressed as

$$
\hat{f}(x) = \sum_{i=1}^{k} c_i B_i(x),
$$

where $B_i$ is the basis function and $c_i$ is a constant coefficient. For the first-order MARS model (in our application), $B_i$ takes one of the following three forms.

1. A constant $1$.
2. A Hinge function $\max(0, x - c)$.
3. A Hinge function $\max(0, c - x)$.

Those segments are joined together at the knots (which are breaks in the light curve in our case). To fit data with the MARS model, the procedure first tries to repeatedly add basis functions to give the maximum reduction in sum-of-squares residual error (so-called $\chi^2$-fitting method), then prunes the model by deleting the least effective term at each step until it finds the best submodel. The latter step involves a “penalty” parameter, $d$, which controls the number of segments and the smoothness of the MARS model. In this work, we tried 20 values of $d$ (uniformly distributed from 0 to 10). We compared the outcome models and chose the best one by using the Bayesian information criterion method (see Osei-Bryson & Ngwenyama 2014 for a detailed overview of MARS technique). An example of showing how $d$ affects the fitting and how we chose the best model is presented in Figure 3.

In Figure 4, we plot two examples of light-curve fitting results from the MARS technique and the XRT GRB online catalog (Evans et al. 2009). It is shown that for bursts without flares (e.g., 150201), the results from the MARS technique are well matched with the results from the XRT GRB online catalog. For bursts with flares (e.g., 060607), the XRT online catalog only fits the light curve by removing the flare features, while the MARS technique could incorporate the flare phases. It is worth noticing that for these bursts, without considering the flare phase, the fitting result from the MARS technique is still consistent with that of the XRT online catalog. For all bursts in our sample, we list the model information (such as fitting parameters, including breaks and slopes) in our online real-time HTML table at http://astrowww.bnu.edu.cn/NewCN/grb/GRB_XRAY_FIT/. For each burst, we have made a link to the UK website for the comparison of our results with those of the XRT online catalog.
In Figure 5, we show some examples of our fitting results for different types of light curves, with marks of $t_{\text{stp}}$ and $t_{\text{pla}}$ (if applicable). The top row of panels (GRB 160321 and GRB 060908) is for the first category, i.e., either with simple power-law decay light curves or with broken power-law decay light curves but without showing any steep decay or plateau signature. The first panel in the middle row (GRB 151022A) is for the second category, i.e., with steep decay features but without showing any flare or plateau features. The other two panels in the middle row (GRB 070420 and GRB 120213A) are for the third category, i.e., consisting of plateau features but without flare features. The bottom row of panels is for the fourth category, i.e., consisting of X-ray flare features in the light curve.

In Figure 5, we show some examples of our fitting results for different types of light curves, with marks of $t_{\text{stp}}$ and $t_{\text{pla}}$ (if applicable), to better illustrate the light-curve properties for each of the four categories.

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