A Comparative Study of the Power-law Relationship between the Pulse width and Energy of Precursor and Main Burst Postprint

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Date: 2024-03-29T00:00:00+00:00

Abstract

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Full Text

Preamble

Research in Astronomy and Astrophysics, 24:035013 (25pp), 2024 March

https://doi.org/10.1088/1674-4527/ad0497

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Received 2022 October 4; revised 2023 March 17; accepted 2023 October 16; published 2024 February 26

Abstract

In gamma-ray burst prompt emission, there is still no consistent conclusion regarding whether the precursor and main burst share the same origin. In this paper, we investigate this issue based on the relationship between pulse width and energy for both precursors and main bursts. We systematically search the light curve data observed by Swift/BAT and Fermi/GBM, and identify 13 long bursts with well-structured precursors and main bursts. After fitting the precursor light curve of each different energy channel with the Norris function, we find not only a power-law relationship between precursor width and energy, but also a power-law relationship between the ratio of the rising width to the decaying width and energy. By comparing these relationships between precursors and main burst pulses, we find that the distributions of precursors and the relationships between the power-law indices are roughly the same as those of the main burst. In addition, we find that the precursor width distribution and the upper limit of the pulse width ratio do not exceed 1, and both are asymmetric, which is also consistent with the main burst. These results indicate that the precursor and the main burst are indistinguishable, suggesting they may have the same physical origin.

Key words: methods: data analysis -(stars:) gamma-ray burst: general -shock waves

1. Introduction

A gamma-ray burst (GRB) is a phenomenon in which the intensity of γ-rays from a certain direction in the sky suddenly increases over a short period and then rapidly weakens, lasting 0.1–1000 s, with radiation mainly concentrated in the 0.1–100 MeV energy band. According to T90, GRBs can be divided into two types: long bursts when T90 is more than 2 s and short bursts when T90 is less than 2 s.

The main event of a GRB is prompt emission. Most theoretical models predict a weaker radiation event before the main event, called a precursor. Almost since the discovery of GRBs, the first case of GRB 720427 containing a precursor was observed with the high-energy spectrometer installed on the Apollo 16 spacecraft (Metzger et al. 1974). Since this dark peak was 3σ above the average background level and much fainter than the other peaks, it was called a "probable precursor" by observers at the time and was considered a mystery because its origin could not be explained.

Koshut et al. (1995) provided the first definition of a precursor: the peak intensity of precursors is somewhat lower than that of the main burst and far away from the main GRB, the intensity of the separation phase (quiescent period) is equal to the background, and the separation distance is not shorter than that of the main burst stage. They ascertained that 3% of BATSE GRBs had precursors as of 1994 May. They found that these GRBs with precursors and other GRBs without precursors had the same spatial distribution, and the duration of the precursors correlated with the duration of the main bursts. However, they identified no other significant connection between the precursors and the main bursts, suggesting that precursors and main GRBs may be independent of each other.

Lazzati (2005) selected bright long BATSE bursts by defining the precursor as follows: first, the precursor must be a radiation event detected before the trigger; second, the flux of this event must decrease before triggering, with searches for precursors performed 200 s before the GRB trigger. The precursor was characterized by a softer spectrum relative to the main burst, and the result showed no correlation between precursor properties and those of the main bursts.

Burlon et al. (2008) (hereafter B08) gave a simpler definition: any peak flux lower than the subsequent main burst and separated from the main event by a quiescent period, which is not necessarily greater than the duration of the main burst radiation and does not necessarily precede the triggering event. With known redshifts of the precursors, they analyzed and compared the spectra of precursors with the time-integrated spectra of prompt emission. They found neither a correlation between the two slopes nor a tendency for the spectra of precursors to be harder or softer than the prompt spectra. They also found that these properties do not depend on the quiescent period. After comparing the spectral indices of the precursor and the main burst, their results showed that the precursor is not an independent phenomenon different from the main burst. Later, Burlon et al. (2009) found from 2704 BATSE observed bursts that 12.5% of the BATSE bursts had one or more precursors. By the fireball model, the spectral analysis mechanism of precursors and main bursts is supported.

Troja et al. (2010) performed a precursor search for a sample of short bursts observed by Swift, with no strict constraints on whether the instrument was triggered or on the interval between the precursor and the main burst. After analyzing the temporal properties and images of the precursor and the main burst, they found no substantial difference between the precursor and the main burst, or between short GRBs with or without precursors.

Hu et al. (2014) selected a sample of 613 joint observations by the Burst Alert Telescope (BAT) and X-Ray Telescope (XRT) on Swift. They did not specifically require the definition of the precursor to have a quiescent time, and used the Bayesian block algorithm to search for GRB precursors observed by Swift/BAT. Through analyzing the energy spectrum of precursors and main bursts, they found the origin of precursors is consistent with that of main bursts.

Charisi et al. (2015) searched 2710 long bursts from the three instruments BATSE, Swift/BAT, and Fermi/Gamma-ray Burst Monitor (GBM). They adopted the basic precursor definition and applied methods used for gravitational wave analysis to identify precursors, main bursts, and post-bursts. They found no correlation in the temporal properties (duration, peak flux, and number of photons) between the main bursts and the precursors.

Zhu (2015) explored the properties of Fermi GRBs with precursors. The precursors they selected comprehensively took into account the methods used by previous researchers to define them and divided them into three categories for separate studies. They found that the physical origins of precursors and main bursts are different, and discussed the implications between the radiation model of GRB precursors and their observation.

Zhang et al. (2018) reported a particularly bright GRB, GRB 160625B, and found a possible different origin between the main burst and the precursor by analyzing the time-resolved spectra of the precursor and the main burst. They suggested that the precursor might be related to the initial iron core collapse.

Zhong et al. (2019) extracted a sample of 18 short bursts with precursors from the 660 short bursts observed by Fermi and Swift, and performed temporal and energy spectrum analysis on this larger sample. They found that precursors and main bursts still exhibit some differences.

Coppin et al. (2020) analyzed the observation data of Fermi/GBM for 11 years and ascertained that 217 bursts had precursors. They found that the duration of the quiescent interval exhibits a bimodal normal distribution, which indicates that these GRBs might have two different progenitor stars.

Li et al. (2021) studied short burst data observed by Swift/BAT and focused on examining short burst events with simultaneous precursor, main burst, and extended radiation, supporting the idea that the three events originated from similar central engine activity.

Recently, Li & Mao (2022) studied 52 long bursts with precursors selected in the Third Swift BAT catalog. They systematically analyzed the temporal properties of precursors and main bursts and deduced that the precursor and the main burst follow the same τp-ω relationship. They indicated that the precursor and the main burst might have the same physical origin.

Therefore, based on the above research progress, there is no unified conclusion as to whether precursors and main bursts have the same origin.

In early statistical analyses, light curves of GRB pulses were found to become narrower at higher energies (Fishman et al. 1992; Link et al. 1993). Fenimore et al. (1995) used the average autocorrelation function to study the average pulse width and showed that the average pulse width of many bursts is well fitted by a power law of energy, with a power-law index of about -0.4. Norris et al. (1996) also found that the average pulse-shape dependence on energy is approximately a power law, consistent with the analysis of Fenimore et al. (1995). This was confirmed by later studies (Piro et al. 1998; Costa 1999; Nemiroff 2000; Norris et al. 2000; Feroci et al. 2001; Crew et al. 2003). Peng et al. (2006) (hereafter P06) also confirmed this and demonstrated that there is a power-law relationship between the ratio of the rising width to the decaying width and energy.

Since there is some evidence that precursors and main bursts may come from the same origin, we speculate that the width of precursors may also show a power-law decrease with energy. Thus, we investigate whether precursors and main bursts have the same origin from the perspective of the temporal structure of precursors and main bursts in relation to energy changes. In this paper, we comprehensively check whether there is a power-law relationship between the width and energy of the precursor and main burst, and whether there is a power-law relationship between the ratio of the rising width to the falling width and energy from the perspective of the precursor and main burst light curves. In addition, we examine the distribution of power-law indices, the relationship between the two power-law indices, and the distribution of widths. We then compare the precursor results with those of the main burst and with the results from P06 to check if the origins of the precursor and main burst are consistent.

This paper is organized as follows. In Section 2, we present the selection criteria and pulse fitting for the precursor GRB sample. In Section 3, we comprehensively check whether there is a power-law relationship between the width and energy of the precursor and main burst, and whether there is a power-law relationship between the ratio of the rising width to the falling width and energy from the perspective of the precursor and main burst light curves. In addition, we obtain the distribution of power-law indices, the relationship between power-law indices, and the distribution of pulse widths for comparing the precursor with the main burst. Finally, discussion and conclusions are provided in Section 4.

2. Sample and Data Analysis

In this paper, we use a definition of a precursor similar to B08: the precursor peak intensity is lower than the subsequent burst, and there is a quiescent phase separation between the precursor and the main burst. The separation phase has no specific duration and is estimated to range from a few milliseconds to several tens of seconds. We do not require the precursor to precede the bursts by a time delay at least as long as the main burst duration, nor do we impose the condition that a precursor did not trigger the detector. Based on this criterion for selecting precursors by visual inspection, we systematically search observations from Swift/BAT from 2004 December to 2022 July and Fermi/GBM from 2008 July to 2022 April, finding a total of 13 GRBs with good pulse shape precursors and main bursts. We select the 64 ms binning light curves. Among them, one GRB event corresponds to two main bursts, resulting in a total of 27 pulses.

2.1. Swift/BAT and Fermi/GBM

Between 2004 December and 2022 July, Swift/BAT detected 1525 GRBs. We searched for precursors in the GRB light curves and identified six GRBs with good pulse shape precursors and main bursts. Among them, one GRB event corresponds to two main bursts, resulting in a total of 13 pulses.

The GRB event data are processed by the standard BAT software with the latest calibration database, and the background is subtracted to build the GRB light curves. Each light curve has five energy channels: 15-25 keV, 25-50 keV, 50-100 keV, 100-350 keV, and 15-350 keV. Each identified precursor pulse can be described by a fast rise and exponential decay (FRED) function (Fishman et al. 1994). For each precursor and main burst, we require that the signal should be detectable in at least three energy channels. In this way, the relationship between pulse width and energy can be studied.

In the Swift/BAT data, there are exactly three energy channels (15-25 keV, 25-50 keV, and 50-100 keV) that detect significant signals, so we choose the light curves for these three energy channels. Moreover, there are a few binning types of light curve data in the Swift/BAT catalog. We compare these light curves and find that 1 s binning could show the FRED characteristics of the precursors more clearly. However, 1 s binning may be relatively coarse, resulting in overlapping pulses. Therefore, we use the 64 ms binning light curve for the analysis.

Fermi/GBM detected 3274 GRBs between 2008 July and 2022 April, and we searched for precursors in the GRB light curves, finding seven GRBs with good pulse shape precursors and main bursts. We select the light curve data of the brightest trigger detector from the official Fermi/GBM website. To be as consistent as possible with the BAT sample, we use a program to select light curve data with four energy channels: 15-25 keV, 25-50 keV, 50-100 keV, and 100-350 keV. According to the different energy channel signals, three or four energy channels are selected to study whether there is a power-law relationship between pulse width, energy, etc. In addition, we also use the program to automatically select the 64 ms binned light curve.

2.2. Precursor Fitting

GRB events can be described by the shape of FRED (Fenimore et al. 1996). We first assume that the precursor has a similar shape to the GRB pulse. Thus, we adopt the function proposed in Norris et al. (2005) (the Norris function) to fit all background-subtracted light curves because we find that this function can well describe the observed profile of a FRED pulse. The fitting function is:

$$I(t) = A \exp\left(-\frac{\tau_1}{t-t_s} - \frac{t-t_s}{\tau_2}\right),$$

where $t > t_s$, A is the maximum intensity of an episode, and t_s is the start time of an episode. The peak time is $t_{peak} = t_s + \sqrt{\tau_1 \tau_2}$. The pulse width is $\omega = \tau_d + \tau_r = \tau_2 (1+4\mu)^{1/2}$, and the pulse asymmetry is $\kappa = \tau_d / \tau_r$, where the rise time is $\tau_r = \tau_2 [(1+4\mu)^{1/2} - 1]/2$, and the decay time is $\tau_d = \tau_2 [(1+4\mu)^{1/2} + 1]/2$, with $\mu = \tau_1 / \tau_2$.

We fit the precursors using a Markov Chain Monte Carlo (MCMC) technique, which has been widely utilized for astronomical data processing (Li 2019). The Norris function is applied to fit the light curve data for each precursor and main burst in different energy channels. The majority of the pulses can be fitted well using this function, and the distributions of the reduced χ^2 for the total samples are displayed in Figure 1. The fitting parameters and the goodnesses of fit are listed in Tables 1 and 2. The error of the fitting parameter has a confidence interval of 1σ. In the Appendix, some light curves of different energy channels of precursors and main bursts are shown in Figures A1–A16. The blue and purple parts correspond to the Swift/BAT and Fermi/GBM data, respectively.

3. Analysis Results

We first examine whether the widths of the precursor and main burst also follow a power-law decrease with energy. Therefore, we use the Norris function to fit the light curve of the precursor and main burst in each different energy channel, and obtain five fitting parameters to calculate the pulse width (full width at half maximum, FWHM), rising width (rFWHM), and decaying width (dFWHM) in each energy channel of the burst.

3.1. Power-law Relationship between Width and Energy

According to the pulse fitting parameters, we first examine the relationship between width and energy of precursors and main bursts for Swift and GBM respectively. Most of the precursors and main bursts display a power-law anticorrelation between precursor width and energy and a power-law correlation between rFWHM/dFWHM and energy. Examples of such relationships are presented in Figure 2. There are 12 parts (six GRB precursors and six main bursts) to Figure 2: each part is composed of two panels, with the upper panel showing the plot of log(FWHM) versus log(E) and the lower panel showing the plot of log(rFWHM/dFWHM) versus log(E) for the same source, where E is the lower energy bound of the four energy channels, as generally adopted in previous works (see, for example, P06 and Fenimore et al. 1995). The widths of most precursors and most main bursts decrease by a power law with energy, accounting for 76.92% and 100% of the total samples, respectively, which is consistent with the relationship between most GRB pulse widths and energy in previous studies, indicating that the time characteristics of the precursor with energy change are the same as those of the main pulse.

3.2. The Distribution of Power-law Indices and the Relationship between Power-law Indices

In order to further study possible correlations between precursor and main burst, we compare the distributions of the associated power-law indices (α_{FWHM} and α_{ratio}). The parameters are listed in Table 3. First, we compare the distributions of α_{FWHM} and α_{ratio} for the two precursor sub-samples Swift/BAT and Fermi/GBM. The median and mean values of the α_{FWHM} distribution for the Swift/BAT precursor samples are -0.42 and -0.42, respectively, while for the main bursts they are -0.23 and -0.32, respectively. Similarly, the median and mean values of the α_{ratio} distribution for the precursor samples are 0.041 and 0.053, respectively, while for the main bursts they are 0.042 and 0.047, respectively.

For the Fermi/GBM precursor samples, the median and mean values of the α_{FWHM} distribution are -0.22 and -0.14, respectively, while those of the main bursts are -0.28 and -0.33, respectively. The median and mean values of the α_{ratio} distribution of the precursor samples are 0.005 and 0.020, respectively, while those of the main bursts are 0.046 and 0.06, respectively. The α_{FWHM} and α_{ratio} distributions of the two sub-samples are shown in Figure 3. It can be seen that there is little difference in the overall distributions of the precursor and main burst, indicating that different detectors but the same channel have little influence on the distribution of power-law index.

We then compare the power-law index distributions of the precursor samples with those of the main burst. The total sample distribution of α_{FWHM} and α_{ratio} of the precursor is shown in Figure 4. The median and mean of the α_{FWHM} distribution of precursors are -0.28 and -0.27, while those of the main bursts are -0.26 and -0.32, respectively. The median and mean of the α_{ratio} distribution of precursors are 0.041 and 0.022, and those of the main burst are 0.045 and 0.054, respectively. This affirms that the distribution of the power-law index of the total precursor sample is very similar to that of the total main burst sample.

As shown in Figure 5, we present the correlation between the power-law indices α_{FWHM} and α_{ratio} for both the precursor and main burst samples. For the precursors, a regression analysis yields $\alpha_{\mathrm{ratio}} = (0.005 \pm 0.021) - (-0.11 \pm 0.05)\alpha_{\mathrm{FWHM}}$, with a correlation coefficient of $r = -0.58$ ($N = 13$). Similarly, for the main bursts, the regression analysis yields $\alpha_{\mathrm{ratio}} = (-0.014 \pm 0.025) - (-0.21 \pm 0.06)\alpha_{\mathrm{FWHM}}$, with a correlation coefficient of $r = -0.68$ ($N = 14$). We find that the two power-law indices of the two samples show moderate correlation, and the trend in the regression slope for both is roughly similar. Therefore, the main bursts are related to precursors.

By analyzing the power-law relationship between FWHM and energy and the power-law relationship between rFWHM/dFWHM and energy, we find that the results can be divided into three types of bursts. Figure 5 displays three distribution regions for the two indices, which are associated with the three classes defined below. Because for a certain energy range the sign of the indices depends on the radiation mechanism (see Figures 1, 2, and 3 in Qin et al. (2005), hereafter Q05), these different regions might correspond to different mechanisms.

The first class consists of bursts that exhibit a power-law anticorrelation between FWHM and energy ($\alpha_{\mathrm{FWHM}} < 0$) and a power-law correlation between rFWHM/dFWHM and energy ($\alpha_{\mathrm{ratio}} > 0$). There are nine precursors in this class, accounting for approximately 69.2% of the total sample, while there are 12 main bursts, accounting for approximately 85.7% of the total sample. The second class consists of bursts that exhibit negative-index power-law relationships between both FWHM and energy ($\alpha_{\mathrm{FWHM}} < 0$) and between rFWHM/dFWHM and energy ($\alpha_{\mathrm{ratio}} \leq 0$). There is one precursor in this class, accounting for approximately 7.7% of the total sample, while there are two main bursts, accounting for approximately 14.3% of the total sample. The third class consists of bursts that exhibit a power-law correlation between FWHM and energy ($\alpha_{\mathrm{FWHM}} \geq 0$). There are three precursors in this class, accounting for approximately 23.1% of the total sample, while there are zero main bursts, accounting for approximately 0% of the total sample. The proportion of class 1 bursts among precursors is relatively high, while the proportions of other classes are relatively low, similar to the main bursts. In addition, they are similar to the results of P06' s study on GRBs. Therefore, these distributions of the precursor and main burst are similar to those studied in P06 and further suggest a common origin for precursors and main bursts.

3.3. The Width Distribution and Width Ratio Distribution

In order to further investigate the relationship between precursor and main burst, we compare the distributions of FWHM and rFWHM/dFWHM. First, we compare the distributions of FWHM and rFWHM/dFWHM of the two sub-samples of Swift/BAT and Fermi/GBM, as shown in Figure 6. From these two sub-samples we can infer: (1) for the BAT sample, the median FWHMs of the precursor in three energy channels are 10.3, 10.5, and 8.1, while those of the main burst are 6.9, 6.7, and 5.9; for the GBM sample, the median FWHMs of the precursor in four channels are 4.0, 2.5, 3.1, and 2.1, while those of the main burst are 7.2, 5.2, 6.2, and 5.8, respectively. Hence the median FWHM of the two sub-samples of precursor and main burst declines roughly with energy. (2) For the BAT sample, the median rFWHM/dFWHM values of the precursor in three energy channels are 0.775, 0.782, and 0.823, while those of the main burst are 0.825, 0.84, and 0.9; for the GBM sample, the median rFWHM/dFWHM values of the precursor in four channels are 0.796, 0.8, 0.767, and 0.814, while those of the main burst are 0.703, 0.734, 0.75, and 0.857, respectively. Therefore, the median rFWHM/dFWHM for the two sub-samples of precursor and main burst increases roughly with energy. (3) The ratio of rising width to falling width of the two sub-samples of precursor and main burst is about the same. (4) For the BAT sample, the maximum values of rFWHM/dFWHM of the precursor emission in three energy channels are 0.89, 0.93, and 0.88, while those of the main burst are 0.93, 0.94, and 0.95, respectively; for the GBM sample, the median rFWHM/dFWHM values of the precursor in four channels are 0.90, 0.92, 0.92, and 0.87, while those of the main burst are 0.89, 0.91, 0.94, and 1, respectively, and the corresponding maximum value of the two samples of the precursor and main burst does not exceed 1. Combining results (1), (2), (3), (4) and the results shown in Figure 6, it can be concluded that the BAT and GBM samples have approximately the same statistical properties, further illustrating that different detectors but the same channel do not affect the distribution of FWHM and rFWHM/dFWHM.

Next, we compare the total sample distributions of FWHM and rFWHM/dFWHM for precursors and main bursts. Figure 7 depicts the distribution of FWHM and rFWHM/dFWHM for 13 GRB samples. We compare the distribution of FWHM and rFWHM/dFWHM of the total precursor samples with that of the main burst and find that: (1) the median FWHM of the precursor decreases with increasing energy (when fitting FWHM and energy with a power law, the index would be negative), and the main burst is consistent with it; (2) the median rFWHM/dFWHM of the precursor increases with increasing energy (when fitting rFWHM/dFWHM and energy with a power law, the index would be positive), and the main burst is consistent with it; (3) the ratio of the rising width to the decaying width of the precursors is about 0.79, while that for the main bursts is about 0.80; the width ratio of the two is almost equal, the precursors observed are asymmetric, and the main burst is consistent with them; (4) the maximum value of rFWHM/dFWHM in the four energy channels of precursor and main burst does not exceed 1; the precursors correspond to 0.93, 0.90, 0.92, and 0.87, respectively, and the main burst is 0.93, 0.94, 0.95, and 1.0, respectively. Furthermore, the largest values of rFWHM/dFWHM for all the GRB pulse samples studied by P06 do not exceed 0.9, indicating that the results of our study are close to those of the GRB pulse. Moreover, this is in agreement with what was predicted previously in Qin et al. (2004), where it was suggested that there is an upper limit to rFWHM/dFWHM of approximately 1.3. It can be concluded from the above analysis that the complete sample of precursors and main bursts has roughly the same statistical characteristics as P06 and Qin et al. (2004), which also indicates that precursors are indistinguishable from main pulses.

The value of rFWHM/dFWHM for the fourth energy band for the main burst of GRB 220305481 is equal to 1 (see Appendix Figure A16 for its fitting diagram). The shape of a pulse is usually asymmetric, but its value appears to be symmetric. From all the fitted light curves of the GRB 220305481 main burst in this energy channel, it can be seen that the fourth channel fit is not very good. However, the light curves fitted above the FWHM are still good and can accurately obtain the value of FWHM. However, we discover that its FWHM is relatively narrower in comparison to other pulses. Also, Zhang et al. (2007) described the phenomenon of wider pulses tending to be more asymmetric. Therefore, narrower pulses tend to be more symmetric.

Based on the above analysis, from the distribution of width of the precursor and main burst, the distribution of the ratio of the rising width and the decaying width, the power-law relationship between the precursor width and the energy, and the distribution and relationship of two power-law indices, it shows that different detectors have little influence on energy channel, and they are very similar to the main burst. It suggests that the precursors and the main bursts are closely related and may have the same physical origin.

4. Discussion and Conclusion

In early statistical analyses, light curves of GRB pulses were found to become narrower at higher energies (Fishman et al. 1992; Link et al. 1993). Norris et al. (1996) also found that the average pulse-shape dependence on energy is approximately a power law, which was confirmed by later studies (Piro et al. 1998; Costa 1999; Nemiroff 2000; Norris et al. 2000; Feroci et al. 2001; Crew et al. 2003). P06 also showed that there is a power-law relationship between FWHM and energy and a power-law relationship between rFWHM/dFWHM and energy in the light curve of a GRB.

In this paper, we search Swift/BAT and Fermi/GBM and find 13 well-identified GRB precursors and main bursts, which also exhibit a power-law anticorrelation between FWHM and energy and a power-law correlation between rFWHM/dFWHM and energy. These indicate that the precursor and main burst may have the same origin.

The distributions of the two power-law indices of six Swift/BAT samples and seven Fermi/GBM samples show little difference in the overall distribution of the precursor and main burst, indicating that different detectors but the same channel have little influence on the distribution of power-law index. Furthermore, there is no significant difference between the power-law index distribution of the total precursor sample and that of the total main pulse. The median and mean of the α_{FWHM} distribution of precursors are -0.28 and -0.27, while those for the main bursts are -0.26 and -0.33, respectively. The median and mean of the α_{ratio} distribution of precursors are 0.041 and 0.022, and those for the main burst are 0.044 and 0.054, respectively. Moreover, the results of P06 are as follows: for the KRL sample, the median of the distribution of α_{FWHM} is -0.277, and α_{ratio} is 0.066; for the Norris sample, the medians of the distribution of α_{FWHM} and α_{ratio} are -0.302 and 0.083, respectively. We find that the power-law index of the total samples is also roughly the same as that of the KRL sample. This affirms that the distribution of the power-law index of the total precursor sample is very similar to that of the total main burst sample.

At the same time, we analyze the relationship between the two power-law indices, α_{FWHM} and α_{ratio}, and find that there is an anticorrelation between them. For the precursors, a regression analysis yields $\alpha_{\mathrm{ratio}} = (0.005 \pm 0.021) - (-0.11 \pm 0.05)\alpha_{\mathrm{FWHM}}$, with the correlation coefficient being $r = -0.58$. Similarly, for the main bursts, the regression analysis yields $\alpha_{\mathrm{ratio}} = (-0.014 \pm 0.025) - (-0.21 \pm$

$0.06)\alpha_{\mathrm{FWHM}}$, with the correlation coefficient being $r = -0.68$. We find that the two power-law indices for both the precursors and main bursts show moderate correlation, and the trend in the regression slope for both is approximately similar. In addition, in the results of the P06 analysis, for the KRL sample, a regression yields $\alpha_{\mathrm{ratio}} = (-0.03 \pm 0.03) - (0.23 \pm 0.06)\alpha_{\mathrm{FWHM}}$, with the correlation coefficient being $r = -0.428$, while for the Norris sample, the analysis produces $\alpha_{\mathrm{ratio}} = (-0.01 \pm 0.04) - (0.29 \pm 0.10)\alpha_{\mathrm{FWHM}}$, with the correlation coefficient being $r = -0.425$. Our findings suggest that the correlation between the α_{FWHM} and α_{ratio} of the precursor and main burst is comparable to that observed in GRB pulses from P06. The negative linear regression slopes of the precursor and main burst show little difference and are closer to the KRL sample in P06. Therefore, their distribution is roughly the same, further illustrating that the precursor and main burst are indistinguishable.

Our analysis of the relationship between the two power-law indices α_{FWHM} and α_{ratio} reveals an anticorrelation between them. We divide the α_{ratio}-α_{FWHM} plane into three regions, namely regions I($\alpha_{\mathrm{FWHM}} < 0$, $\alpha_{\mathrm{ratio}} > 0$), II($\alpha_{\mathrm{FWHM}} < 0$, $\alpha_{\mathrm{ratio}} \leq 0$), and III($\alpha_{\mathrm{FWHM}} \geq 0$) (see Figure 5). Sources inside these regions are defined as classes 1, 2, and 3, respectively. The proportion of each class of precursors is 69.2%, 7.7%, and 23.1%, respectively, while the proportion of main bursts is 85.7%, 14.3%, and 0%. Due to the small sample size, only the proportions of the distribution of each class in the main burst and P06 are highly similar, and the main burst accounts for approximately 0% in class 3. However, the proportion of class 1 bursts of the precursor is relatively high, while the proportions of other classes are relatively low, similar to the main bursts. In addition, they are similar to the results of P06' s study on GRBs. Therefore, these distributions of the precursor and main burst are similar to those studied in P06 and further suggest a common origin for precursors and main bursts.

The median FWHM of the two sub-samples of precursor and main burst declines roughly with energy, and the median rFWHM/dFWHM increases roughly with energy. Moreover, the ratio of rising width to falling width of the two sub-samples of precursor and main burst is about the same. It appears from Figures 3 and 6 that the detector has some impact on the distribution of data. Specifically, it seems that the BAT and GBM samples are not strongly correlated. However, it should be noted that different detectors detecting different bursts do not affect the close relationship between precursors and main bursts. It can be concluded that BAT and GBM samples have roughly the same statistical characteristics. Consequently, they are distributed similarly, providing further evidence of a correlation between the origins of the precursor and main burst.

We also compare the distribution of FWHM and rFWHM/dFWHM of the total precursor samples with that of the main pulse. First, the median FWHM of the precursor decreases with increasing energy, while the median rFWHM/dFWHM increases with increasing energy, and the main burst is consistent with it. Second, the ratio of the rising width to the decaying width of the precursor is about 0.79, while that for the main burst is about 0.80; the width ratio of the two is almost equal, the precursors observed are asymmetric, and the main burst is consistent with them. Third, the maximum value of rFWHM/dFWHM in the four energy channels of precursor and main burst does not exceed 1; the precursors correspond to 0.93, 0.90, 0.92, and 0.87, respectively, and the main burst is 0.93, 0.94, 0.95, and 1.0, respectively. Furthermore, the largest values of rFWHM/dFWHM for all the GRB pulse samples studied by P06 do not exceed 0.9, indicating that the results of our study are close to those of the GRB pulse. Moreover, this is in agreement with what was predicted previously in Qin et al. (2004), where it was suggested that there is an upper limit to rFWHM/dFWHM of approximately 1.3. It can be concluded from the above analysis that the complete sample of precursors and main bursts has roughly the same statistical characteristics as P06 and Qin et al. (2004), which also indicates that precursors are indistinguishable from main pulses.

There are many authors who analyze the spectral and temporal characteristics of precursors and main bursts to support the idea of the same origin. However, there is still much evidence that does not support the precursor and main burst having the same origin, and more evidence is still needed. For example, Zhang et al. (2018) found a possible different origin between the main burst and the precursor by analyzing the time-resolved spectra of the GRB 160625B precursor and the main burst, and suggested that the precursor might be related to the initial iron core collapse. In the future, we will analyze the characteristics of precursors and main bursts from the perspective of the energy spectrum to further clarify whether they have the same origin.

Acknowledgments

We acknowledge the use of public data from the Fermi and Swift data archives. This work is supported by the National Natural Science Foundation of China (NSFC, Grant Nos. 12163007, 11763009), the Key Laboratory of Colleges and Universities in Yunnan Province for High-energy Astrophysics, and the National Astronomical Observatories, Yunnan Normal University Astronomical Education Base.

Appendix

The Light Curve Fitting Diagrams

The fitting plots for each energy channel of precursors and main bursts' light curves.

Figure A1. Shows the light curves of GRB 091208B precursor for the first, second, and third energy channels in turn (from top to bottom and from left to right).

Figure A2. Shows the light curves of GRB 091208B main burst for the first, second, and third energy channels in turn (from top to bottom and from left to right).

Figure A3. Shows the light curves of GRB 130722A precursor for the first, second, and third energy channels in turn (from top to bottom and from left to right).

Figure A4. Shows the light curves of GRB 130722A main burst for the first, second, and third energy channels in turn (from top to bottom and from left to right).

Figure A5. Shows the light curves of GRB 180325A precursor for the first, second, and third energy channels in turn (from top to bottom and from left to right).

Figure A6. Shows the light curves of GRB 180325A main burst for the first, second, and third energy channels in turn (from top to bottom and from left to right).

Figure A7. Shows the light curves of GRB 200906A precursor for the first, second, and third energy channels in turn (from top to bottom and from left to right).

Figure A8. Shows the light curves of GRB 200906A main burst for the first, second, and third energy channels in turn (from top to bottom and from left to right).

Figure A9. Shows the light curves of GRB 100116897 precursor for the first, second, third, and fourth energy channels in turn (from top to bottom and from left to right).

Figure A10. Shows the light curves of GRB 100116897 main burst for the first, second, third, and fourth energy channels in turn (from top to bottom and from left to right).

Figure A11. Shows the light curves of GRB 130815660 precursor for the first, second, third, and fourth energy channels in turn (from top to bottom and from left to right).

Figure A12. Shows the light curves of GRB 130815660 main burst for the first, second, third, and fourth energy channels in turn (from top to bottom and from left to right).

Figure A13. Shows the light curves of GRB 190310398 precursor for the first, second, third, and fourth energy channels in turn (from top to bottom and from left to right).

Figure A14. Shows the light curves of GRB 190310398 main burst for the first, second, third, and fourth energy channels in turn (from top to bottom and from left to right).

Figure A15. Shows the light curves of GRB 220305481 precursor for the first, second, third, and fourth energy channels in turn (from top to bottom and from left to right).

Figure A16. Shows the light curves of GRB 220305481 main burst for the first, second, third, and fourth energy channels in turn (from top to bottom and from left to right).

References

Burlon, D., Ghirlanda, G., Ghisellini, G., et al. 2008, ApJL, 685, L19
Burlon, D., Ghirlanda, G., Ghisellini, G., Greiner, J., & Celotti, A. 2009, A&A, 505, 569
Charisi, M., Márka, S., & Bartos, I. 2015, MNRAS, 448, 2624
Coppin, P., de Vries, K. D., & van Eijndhoven, N. 2020, PhRvD, 102, 103014
Costa, E. 1999, NuPhS, 69, 646
Crew, G. B., Lamb, D. Q., Ricker, G. R., et al. 2003, ApJ, 599, 387
Fenimore, E. E., in ' t Zand, J. J. M., Norris, J. P., Bonnell, J. T., & Nemiroff, R. J. 1995, ApJL, 448, L101
Fenimore, E. E., Madras, C. D., & Nayakshin, S. 1996, ApJ, 473, 998
Feroci, M., Antonelli, L. A., Sofitta, P., et al. 2001, A&A, 378, 441
Fishman, G. J., Meegan, C. A., Wilson, R. B., et al. 1992, in AIP Conf. Ser. 265, ed. W. S. Paciesas & G. J. Fishman (Melville, NY: AIP), 13
Fishman, G. J., Meegan, C. A., Wilson, R. B., et al. 1994, ApJS, 92, 229
Hu, Y.-D., Liang, E.-W., Xi, S.-Q., et al. 2014, ApJ, 789, 145
Koshut, T. M., Kouveliotou, C., Paciesas, W. S., et al. 1995, ApJ, 452, 145
Lazzati, D. 2005, MNRAS, 357, 722
Li, L. 2019, ApJS, 242, 16
Li, L., & Mao, J. 2022, ApJ, 928, 152
Li, X. J., Zhang, Z. B., Zhang, X. L., & Zhen, H. Y. 2021, ApJS, 252, 16
Link, B., Epstein, R. I., & Priedhorsky, W. C. 1993, ApJL, 408, L81
Metzger, A. E., Parker, R. H., Gilman, D., Peterson, L. E., & Trombka, J. I. 1974, ApJL, 194, L19
Nemiroff, R. J. 2000, ApJ, 544, 805
Norris, J. P., Bonnell, J. T., Kazanas, D., et al. 2005, ApJ, 627, 324
Norris, J. P., Marani, G. F., & Bonnell, J. T. 2000, ApJ, 534, 248
Norris, J. P., Nemiroff, R. J., Bonnell, J. T., et al. 1996, ApJ, 459, 393
Peng, Z. Y., Qin, Y. P., Zhang, B. B., et al. 2006, MNRAS, 368, 1351
Piro, L., Heise, J., Jager, R., et al. 1998, A&A, 329, 906
Qin, Y. P., Dong, Y. M., Lu, R. J., Zhang, B. B., & Jia, L. W. 2005, ApJ, 632, 1008
Qin, Y. P., & Lu, R. J. 2005, MNRAS, 362, 1085
Qin, Y.-P., Zhang, Z.-B., Zhang, F.-W., & Cui, X.-H. 2004, ApJ, 617, 439
Troja, E., Rosswog, S., & Gehrels, N. 2010, ApJ, 723, 1711
Zhang, B. B., Zhang, B., Castro-Tirado, A. J., et al. 2018, NatAs, 2, 69
Zhang, Z. B., Xie, G. Z., Deng, J. G., & Wei, B. T. 2007, AN, 328, 99
Zhong, S.-Q., Dai, Z.-G., Cheng, J.-G., Lan, L., & Zhang, H.-M. 2019, ApJ, 884, 25
Zhu, S. J. 2015, *Precursors in gamma-ray bursts observed by Fermi*, PhD thesis, Univ. Maryland, College Park