MEASURING THE PULSE OF GRB 090618: A SIMULTANEOUS SPECTRAL AND TIMING ANALYSIS OF THE PROMPT EMISSION

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ABSTRACT

We develop a new method for simultaneous timing and spectral studies of gamma-ray burst (GRB) prompt emission and apply it to make a pulse-wise description of the prompt emission of GRB 090618, the brightest GRB detected in the Fermi era. We exploit the large area (and sensitivity) of Swift/Burst Alert Telescope and the wide bandwidth of Fermi/Gamma–ray Burst Monitor to derive the parameters for a complete spectral and timing description of the individual pulses of this GRB, based on the various empirical relations suggested in the literature. We demonstrate that this empirical model correctly describes the other observed properties of the burst, such as the variation of the lag with energy and the pulse width with energy. The measurements also show an indication of an increase in the pulse width as a function of energy at low energies for some of the pulses, which is naturally explained as an off-shoot of some particular combination of the model parameters. We argue that these model parameters, particularly the peak energy at the beginning of the pulse, are the natural choices to be used for correlation with luminosity. The implications of these results for the use of GRBs as standard candles are briefly described.

Key words: gamma-ray burst: general – gamma-ray burst: individual (GRB 090618) – methods: data analysis – methods: observational

1. INTRODUCTION

The phenomenon of gamma-ray burst (GRB) has raised many unresolved issues. For example, the nature of the compact object in the progenitor responsible for the jet emission is not yet understood. The widely accepted scenario for GRB emission, supported by strong observational evidence (van Paradijs et al. 2000), is that of a catastrophic energy release from a highly massive, rapidly rotating, and low-metallicity star towards the end of its life. This catastrophic process for the long GRB class ($T_{90} \geq 2$ s, where $T_{90}$ is the time taken by the burst to accumulate between 5% and 95% of its prompt emission; see Kouveliotou et al. 1993; Norris et al. 2005) is attributed to the collapsar or hypernova scenario (Woosley 1993; Paczynski 1998; Fryer et al. 1999; Mészáros 2006a, 2006b), while the short GRBs ($T_{90} \lesssim 2$ s) are thought of as the outcome of merging neutron star binaries or neutron-star–black-hole binaries (Paczynski 1986; Meszaros & Rees 1992, 1997; Rosswog & Ramirez-Ruiz 2003; Rosswog et al. 2003). Though the collapsar model supports the formation of a stellar mass black hole, it is also suggested that the compact object could be a magnetar (Metzger et al. 2007; Metzger 2010).

The prompt emission of long GRBs shows a wide range of structures in their light curve, though the time-integrated energy spectra are adequately fit by a four-parameter Band model (Band et al. 1993). Attempts have been made to fit the light curve of the prompt emission with empirical models such as the Fast Rise Exponential Decay (FRED) model (Kocevski et al. 2003) and the exponential model (Norris et al. 2005). These models assume an underlying pulse structure of the prompt emission. The curve fitting shows that the pulses are nearly simultaneous in a wide range of energy bands (Norris et al. 2005) and have self-similar shapes (Nemiroff 2000). Hakkila & Preece (2011) showed that the observed properties of the short pulses of long GRBs correlate in the same way as typical pulses of short GRBs. All these properties of pulse emission indicate that despite being diverse in their many features, the prompt emission of GRB has a simple underlying mechanism of pulse emission which can be characterized by empirical models irrespective of the progenitor or the environment of its formation (Hakkila & Preece 2011).

The properties of the prompt emission of GRBs, such as $E_{peak}$ (the energy at which the emission peaks; Amati et al. 2002), the lag between the light curves at two energies (Norris et al. 2000), the average variability seen during the prompt emission (Fenimore & Ramirez-Ruiz 2000), and the rise time of the pulses (Schaefer 2002), are found to be correlated to the luminosity of the bursts and hence they are used as distance indicators (Schaefer 2007; Gehrels et al. 2009). Most of these derived relations are empirical in nature and the analyses that are done to derive these parameters, however, are done separately in the time or the energy domain. For example, to derive $E_{peak}$ the time-integrated spectrum is used, ignoring the time variability and the pulse characteristics. Similarly, to derive lags, the time profile is examined in a few broad energy bands. Attempts have been made to investigate the variations of these derived parameters in the other domain. For example, the variation of $E_{peak}$ with time has been investigated by Kocevski & Liang (2003). A complete empirical description of GRB prompt emission which describes the time as well as energy distribution, however, is lacking. This is probably due to the method of spectral parameter determination which is forward in nature: that is one assumes a possible spectral model, convolves with the detector response, and verifies the validity of the model by comparing with the data (Arnaud 1996). Hence, it is difficult to incorporate time variability parameters in this scheme. GRBs often have overlapping pulses which further complicates the extracting of model parameters for any unified empirical description.

In this paper, we develop a technique to give a complete pulse-wise empirical description of the prompt emission of a GRB using the time-integrated spectrum and the energy-integrated light curve. We apply this method to the Fermi/Gamma–ray Burst Monitor (GBM) and the Swift/Burst Alert Telescope (BAT) data of GRB 090618, which has the highest fluence among all 438 GBM GRBs until 2010 March (Nava et al. 2011). We exploit the large area of Swift/BAT to obtain accurate light curves and the large bandwidth of Fermi/GBM to obtain...
accurate energy spectra. We use the Band description for the time-integrated spectral model (Band 2003) and the exponential model (Norris et al. 2005) for the energy-integrated timing description for the pulses. We use the expression for the variation of $E_{\text{peak}}$ with time given by Kocevski & Liang (2003) and develop a method to derive the model parameters (see Section 4.1.2). We demonstrate that these model parameters correctly describe the variation of pulse width with energy and the variation of the lag with energy.

In Section 2 we give a brief description of GRB 090618, and in Section 3 we give the data analysis techniques including spectral analysis (Section 3.1), timing analysis (Section 3.2), and a pulse-wise joint ($\text{Swift}/\text{BAT}$ and $\text{Fermi}/\text{GBM}$) spectral analysis (Section 3.3). In Section 4 we describe our method in detail, which gives a complete three-dimensional pulse-wise description of the GRB. The model-predicted timing results are compared with the observations in Section 4.2 and the implications for global correlations are touched upon in Section 4.3. The results are discussed and the major conclusions are given in the last section (Section 5).

2. GRB 090618

The brightest GRB in the $\text{Fermi}$ era (as of 2010 March), GRB 090618, was simultaneously observed with $\text{Swift}/\text{BAT}$ (Schady 2009; Schady et al. 2009a, 2009b), $\text{AGILE}$ (Longo et al. 2009), $\text{Fermi}/\text{GBM}$ (McBreen 2009), $\text{Suzaku}/\text{Wide-band}$ All-sky Monitor (WAM) (Kono et al. 2009), $\text{Wind}/\text{Konus-Wind}$, $\text{Coronas-Photon}/\text{Konus-RF}$ (Golenetskii et al. 2009), and $\text{Coronas-Photon}/\text{RT-2}$ (Rao et al. 2009, 2011). This is a long GRB ($T_{90} \sim 113$ s) with a fluence of $3398.1 \pm 62.0 \times 10^{-7}$ erg cm$^{-2}$ (integrated over $\Delta t = 182.27$ s). The detection time reported by $\text{Swift}/\text{BAT}$ is 2009 June 18 at 08:28:29.85 UT (Schady 2009) whereas the $\text{Fermi}/\text{GBM}$ detection time is 08:28:26.66 UT (McBreen 2009). This burst showed structures in the light curve with four peaks along with a precursor. A significant spectral evolution was also observed in the prompt emission which lasted for about 130 s from the trigger time (for a summary see Rao et al. 2011).

The $\text{GRB}$ afterglow was observed in the softer X-rays and optical regions. The optical afterglow was tracked by Palomar 60 inch telescope (Cenko 2009), Katzman Automatic Imaging Telescope (Perley 2009), followed by various other optical, infrared, and radio observations. Observations using the Kast spectrograph on the 3 m Shane telescope at Lick Observatory (Cenko et al. 2009) revealed a redshift of $z = 0.54$ (Cenko et al. 2009). The X-ray afterglow was measured by the $\text{Swift}/\text{X-Ray}$ Telescope (Schady et al. 2009a). Initially very bright in the X-rays, the flux rapidly decayed with a slope of $\sim 6$ before breaking after 310 s from the trigger time when the burst entered a shallower decay phase (slope $0.71 \pm 0.02$—Beardmore & Schady 2009).

Rao et al. (2011) analyzed the prompt emission of GRB 090618 using $\text{Coronas-Photon}/\text{RT-2}$ and $\text{Swift}/\text{BAT}$ data. The light curves in various energy bands were fitted with a FRED profile to identify pulse characteristics such as width, peak position, etc. A joint $\text{RT-2}$ and $\text{BAT}$ spectral analysis of individual pulses was done using the spectral model of Band. The reported time-integrated low-energy photon index ($\alpha$), the high-energy photon index ($\beta$), and the peak energy ($E_{\text{peak}}$) are $-1.40, -2.50,$ and $164$ keV, respectively. Ghirlanda et al. (2010) performed a time-resolved spectral analysis of $\text{Fermi}$ GRBs of known redshifts (GRB 090618 being one of the twelve in the list) to show that the time-resolved correlation ($E_{\text{peak}} - L_{\text{iso}}$) within individual GRBs is consistent with time-integrated correlation ($E_{\text{peak}} - L_{\text{iso}}$), indicating that there must be a physical origin for the correlation and may not be an outcome of instrumental selection effects.

3. DATA ANALYSIS

We used $\text{Fermi}/\text{GBM}$ and $\text{Swift}/\text{BAT}$ data for our analysis. The GBM consists of twelve sodium iodide (NaI: $n_{x}$ where $x$ runs from 0 to 11) and two bismuth germanate (BGO: by, where $y$ runs from 0 to 1) detectors. The NaI covers the energy range $\geq 8$ keV to $\sim 1$ MeV while the BGO covers a wider range of $\sim 200$ keV to $\sim 40$ MeV. Data are saved in three types of packets (Meegan et al. 2009): (1) time tag events (TTE) in which time and energy information (in 128 energy channels) of individual photons are stored, (2) CSPEC: binned data in 1.024 s bins and 128 energy channels, and (3) CTIME: binned data in 0.064 s bins and 8 energy channels (which is not suitable for spectroscopy). The triggered detectors for the GRB 090618 were $n_4, n_7, b_0,$ and $b_1$. In the following analysis we have used $n_4, n_7,$ and either $b_0$ or $b_1,$ one at a time. On the other hand, BAT has an array of CdZnTe detector modules located behind a coded aperture mask. This covers an energy range of 15–150 keV (Barthelmy et al. 2005; Gehrels et al. 2004). The large area of BAT (5200 cm$^2$) gives very good sensitivity for timing analysis, compared to that of NaI/BGO (126 cm$^2$) detectors of GBM.

3.1. Spectral Analysis

Ghirlanda et al. (2010) have presented the time-resolved spectral analysis results for GRB 090618 in 14 time segments. We essentially followed the same methodology, but have also used the simultaneous $\text{Swift}/\text{BAT}$ data. GRB 090618 triggered the $\text{Swift}/\text{BAT}$ instrument on 2009 June 18 at 08:28:29.851 or 267006514.688 MET (s). The $\text{Fermi}/\text{GBM}$ trigger time is $T_0(\text{GBM}) = 2009$ June 18 08:28:26.659 UT or 267006508.659 MET (s). Hence, there is a delay time in the BAT data file which must be subtracted during the joint analysis. The calculated time delay is $-3.192$ s and when we convert it to MET it gives 267006511.496 MET (s) for $\text{Swift}/\text{BAT}$. Throughout the analysis this time is subtracted from the trigger time unless specified otherwise.

For the GBM we chose the TTE files of the triggered NaI detectors, namely, $n_4$ and $n_7$. The BGO detector was excluded as it is not suitable for time-resolved spectroscopy owing to its lower sensitivity (Ghirlanda et al. 2010). The energy range was chosen to be $\geq 8$ keV to $\sim 900$ keV. We used $\text{RMFIT}$ package provided by the User Contributions of the Fermi Science Support Center (FSSC) to select the desired time cuts and for generating the background files. The background was taken before and after the burst, avoiding burst contamination; and the exposure time for the background was optimized for different detectors. The energy channels were binned so as to get a minimum of 40 counts per channel. For the analysis of the BAT data we used standard tasks prescribed in The $\text{Swift}$ BAT Software Guide, V ersion 6.3 of Hasoef 6.9, employing a time delay of $-3.192$ s.

These spectra were then fitted with a cutoff power law of the form $F = c \cdot x \cdot E^\alpha \exp(-E/E_0)$, where $F$ is the photon flux. The constant factor, $c$, was kept free while fitting essentially to take care of the different systematic errors in the area calibration of the two instruments. The derived parameter values (using GBM alone) were found to be consistent with...
the values presented in Ghirlanda et al. (2010). Figure 1 shows the comparison results of the spectral analysis. In Figure 1 (left panel), the indices $\alpha$ obtained from the joint analysis are plotted against those obtained from an analysis of the GBM data for the 14 different time segments. Similar data for the parameter $E_0$ are shown in the right panel. A deviation is noted for the parameter $\alpha$ in the 0–3 s region. This may be attributed to the lower count rate of BAT in the precursor region.

We note a systematic increment in the value of $\alpha$ and $E_0$ after the inclusion of BAT data. Further, the constant factor is always lower by 10%–20% for BAT. Sakamoto et al. (2011) have made a joint spectral analysis of 14 GRBs using data from Swift/BAT, Konus/Wind and Suzaku/WAM and they have noted that for the BAT data, the constant factor is systematically lower by 10%–20%, the photon index is steeper by 0.1–0.2, and $E_{\text{peak}}$ becomes higher by 10%–20%. The results presented here are in general agreement with those conclusions.

In Figure 2, we have plotted the ratio of fractional errors as a function of the measured parameters. We find that there is a marginal improvement for the parameter $E_0$ (Figure 2, right panel). The parameter $\alpha$ (Figure 2, left panel), however is always measured with a greater accuracy from the joint analysis. The large effective area of BAT improves the accuracy of the spectral index, whereas its low high energy threshold ($\sim 150$ keV) has a relatively low impact on the measurement of the high energy cutoff value. The joint analysis always gives confidence in the measured parameters and ensures that the effects of instrumental artifacts are minimized. Hence we use, in the later analysis, a joint fit for measuring the global spectral parameters and use only the BAT data for a joint timing and spectral analysis.

### 3.2. Timing Analysis

We identified four pulses (other than the precursor) in the $\sim 60$ s to $\sim 130$ s period after the trigger. Both Swift/BAT and Fermi/GBM (n4) were used for the timing analysis. We subtracted the background and shifted the time origin to the trigger time (TRIGTIME is the keyword in the header) of the respective satellite. As we noted previously, there is a time lag of $\sim 3.192$ s for the BAT trigger. Light curves were extracted for different energy bands for both data sets. The energy bands for Swift/BAT were 15–25 keV, 25–50 keV, 50–100 keV, and 100–200 keV. For Fermi/GBM (n4), we chose...
Norris et al. (2005): BGO detector of GBM were excluded because the third and the fourth pulses (lower panels of Figure 3). We fitted these data for the individual pulses with (1) constant ($w = c$) and (2) linear ($w = mE + c$) models. For the first two pulses, there was a significant improvement in the $\chi^2$ for a linear fit (the $\chi^2$ varied from 16.2(9) to 5.1(8) and 140.9(9) to 7.9(8), respectively for the two pulses; the numbers in the parentheses are the degrees of freedom). The derived slopes are $(-7.4 \pm 2.6) \times 10^{-3}$ s keV$^{-1}$ and $(-5.5 \pm 0.4) \times 10^{-3}$ s keV$^{-1}$, respectively, for the two pulses. The third and the fourth pulses, however, showed negligible improvement in $\chi^2$ from (8.7(9) to 6.0(8) and 2.1(8) to 2.1(7), respectively, for the two pulses) for the linear fit. For these two pulses, when the data below 70 keV is considered, there is a marginal improvement in $\chi^2$ for a linear fit with a positive slope (from 8.7(9) to 3.8(5) and 2.1(8) to 1.5(5), respectively, for the two pulses). The derived slopes are $(15 \pm 14) \times 10^{-3}$ s keV$^{-1}$ and $(10 \pm 21) \times 10^{-3}$ s keV$^{-1}$, respectively. Though the slopes for these two pulses are positive, the error bars are quite large and hence the evidence of this reverse variation is tentative. In Figure 3 (lower two panels), the linear fits for pulses 3 and 4 are shown by solid lines (in the low energy) and dot-dashed lines (in full energy band). We have ignored the fourth pulse in the 200–500 keV band of Fermi for the fitting as it was not prominent in this energy band.

### 3.3. Pulse-wise Joint Spectral Analysis

The peak position and the width gave a clue for the time cut for each pulse and facilitated the selection of integration time for pulse spectral analysis of the individual pulses. The pulse spectral analysis was done with a Band function fit and including the BGO detector of GBM. We included the precursor pulse in this analysis. We divided the GRB event into four time segments, namely, Part 1 ($T_0$ to $T_0 + 50$), Part 2 ($T_0 + 50$ to $T_0 + 77$), Part 3 ($T_0 + 77$ to $T_0 + 100$), and Part 4 ($T_0 + 100$ to $T_0 + 180$). The first and second pulses are considered together as there is too much overlap between them.

All spectra were fitted in the energy range $\sim 8$ keV to $\sim 1$ MeV with the four-parameter model of Band et al. (1993):

$$I(E) = \begin{cases} A_b \left[ \frac{E}{m} \right]^{\alpha} \exp \left[ \frac{-2m(\alpha - \beta)}{E_{\text{peak}}} \right] & \text{if } E \leq [(\alpha - \beta)/(2 + \alpha)]E_{\text{peak}} \\ A_b \left[ \frac{E}{m} \right]^{\beta} \exp \left[ \beta - \alpha \right] \left[ \frac{(\alpha - \beta)E_{\text{peak}}}{100274\alpha} \right]^{(\alpha - \beta)} & \text{otherwise.} \end{cases}$$

The lower and higher energy parts are characterized by the parameters $\alpha$ and $\beta$, respectively, and they meet smoothly at the spectral break energy $[(\alpha - \beta)/(2 + \alpha)]E_{\text{peak}}$. The peak energy, $E_{\text{peak}}$, or equivalently the characteristic energy, defined as $E_0 = E_{\text{peak}}/(2 + \alpha)$, may be considered as the third parameter.
of the model. The best-fit model parameters along with the nominal 90% confidence level error ($\Delta \chi^2 = 2.7$) for the joint fit of Fermi/GBM (n4, n7, b1) and Swift/BAT are reported in Table 1 (b0 in place of b1 gives similar results). The high-energy photon index $\beta$ is constrained primarily by the GBM data and hence we have kept its value fixed at $-2.5$ to determine precise values of $E_{\text{peak}}$ and $\alpha$. Only in one case, namely, for the full range ($T_0$ to $T_0 + 180$ s) of the GRB, $\beta$ was made to vary and a value of $-2.96$ was obtained. Figure 4 shows the joint Band spectral fitting of this range along with the $\chi^2$ deviation of the data.

An examination of the residuals in Figure 4 reveals that there are some systematic differences in the response in the 20–40 keV region between BAT and GBM data and the resultant $\chi^2$ values generally are quite high. The resultant spectral parameters, however, agree with the results reported for this GRB (Ghirlanda et al. 2010; Nava et al. 2011; Rao et al. 2011). The errors are generally are quite high. The resultant spectral parameters, namely $n_4$ and $n_7$ have the spectrum above 8–800 keV. The extreme channels and specifically the 25th channel of $n_4$ are ignored due to high background rates. The unfolded spectrum of BAT shows a lower normalization (see the text).

![Figure 4. Fitting of the Band function to the full range (0–180 s) of GRB 090618 for the energy range ~8 keV to ~1 MeV. The range of the BGO detector starts above 200 keV, while BAT covers up to ~150 keV. The other two detectors namely n4 and n7 have the spectrum above 8–800 keV. The extreme channels and specifically the 25th channel of n4 are ignored due to high background rates. The unfolded spectrum of BAT shows a lower normalization (see the text).](image)

4. JOINT SPECTRAL AND TIMING STUDY: AN ALTERNATIVE APPROACH

4.1. Two-parameter XSPEC Table Model

4.1.1. The Time Evolution of $E_{\text{peak}}$

The light curve of each pulse of a GRB can be described in terms of the four-parameter model of Norris (Equation (1)) and the spectrum for each pulse can be fitted with the Band model (Equation (2)). Liang & Kargatis (1996) showed for clean, separable pulses that the peak energy of the $\nu F_\nu$ spectrum, $E_{\text{peak}}$, decays with the photon fluence as

$$E_{\text{peak}}(t') = E_{\text{peak},0}e^{-\phi(t')/\phi_0},$$  \hspace{1cm} (3)

where $E_{\text{peak},0}$ is the peak energy at zero fluence, $\phi_0$ is the decay constant, and $t' = t - t_s$. The quantity $\phi(t')$ is the fluence up to time $t$ from the start of the pulse ($t_s$). For convenience of description we shift our origin to $t_s$ and hence $t' = t$ for each pulse analysis. Equation (3) quantifies the overall softening of the burst with time.

Kocevski & Liang (2003) have integrated the light curves of a sample of GRBs up to various times $t$ and found the fluence, $\phi(t)$, at those times. The peak energy at the same times, $E_{\text{peak}}(t)$, was found by fitting the spectra with a Band model. They determined $E_{\text{peak},0}$ and $\phi_0$ from a semi-log plot of $E_{\text{peak}}(t)$ versus $\phi(t)$ and fitting a straight line. This procedure was adopted for clean, bright, and separable FRED pulses.

Here we explore a method to determine the timing and spectral parameters by assuming that $E_{\text{peak}}(t)$ and $\phi(t)$ are related according to Equation (3) in each pulse. Essentially we assume that for each pulse, the variation of flux with time is given by the exponential model (Equation (1)), and at each time the spectra are described by a Band function (Equation (2)), and, for a given pulse, only the peak energy varies with time governed by Equation (3). We develop a method to derive the model parameters from a time-integrated spectrum and energy-integrated light curve.

4.1.2. Description of the Method

The flux of a GRB pulse is a function of time and energy. If there exist empirical formulae for the temporal and spectral behavior then the flux can be described in terms of all the model parameters. For example, the variation of flux with time is given by Norris’ exponential model, with four parameters ($A_0$, the normalization, $t_0$, $t_1$, and $t_2$). The spectral behavior is parameterized by a Band function, with four parameters ($A_0$, the normalization, $\alpha$, $\beta$, and $E_{\text{peak}}$). For any timing model, the time parameters change with energy, e.g., the derived parameter, width, changes in various energy bands (see Section 3.2). Similarly, the spectral parameters of any spectral model change with time, e.g., $\alpha$ and $E_0$ of cutoff power law change with time in the same pulse (see Section 3.1).

The Norris exponential model (Equation (1)) describes the evolution of a pulse with time. This description can be used for counts in any energy band and the variation of the model parameters with energy can be studied. Instead, we assume that the model parameters $t_1$ and $t_2$ derived for a pulse integrated over all energy bands are global parameters describing the evolution of total flux with time. Since the variation of spectrum is best described by the peak energy evolution with fluence (Equation (3)), we further assume that $\alpha$ and $\beta$ do not change with time. The normalization factors ($A_0$, and $A_0$) are related by the fact that the fluence calculated either by time integration of the pulse light curve or by the integration over the total energy should be the same. With these assumptions, the parameters for a given pulse are determined as follows.

For a given pulse, we use the energy-integrated light curve from BAT and use Equation (1) for the fitting. This best-fit light curve is used to determine the global parameters, namely, $A_0$, $t_1$, and $t_2$. Since we can arbitrarily choose the pulse starting time by shifting the time origin, the parameter $t_0$ is not very relevant (also see Section 4.1.1). This function is then integrated up to a time $t$ to determine $\phi(t)$. From the individual spectral fitting for each pulse using the Band model, $\alpha$ and $\beta$ are determined (see Section 3.3). Now, if the constant parameters, namely, $E_{\text{peak},0}$ and $\phi_0$ are determined, we have a complete spectral and timing description of a GRB pulse. For this purpose, we use a
For a particular combination of $E_{\text{peak},0}$ and $\phi_0$ values, $E_{\text{peak}}(t)$ at any time $t$ can be determined from Equation (3). On the other hand, Equation (2) can be rewritten as $I(E) = A_n f(E)$, where $A_n$ is the normalization and $f(E)$ is the rest of the functional form valid in the two energy bands. Given the global parameters $\alpha$ and $\beta$ and the time-dependent parameter ($E_{\text{peak}}(t)$), $f(E)$ can be determined. The normalization $A_n(t)$ can be found by dividing the fluence ($\phi(t)$) of the light curve by $f(E)$ integrated over the whole energy range. Hence photon spectrum is generated for the time instance $t$. Choosing a time and energy grid, counts can be plotted as a function of time and energy for a particular combination of $E_{\text{peak},0}$ and $\phi_0$ values, and the resulting surface can be referred to as a three-dimensional pulse model. Hence, for a two-dimensional grid of guess values of $E_{\text{peak},0}$ and $\phi_0$ we can generate three-dimensional pulse models for each of the grid points. These model pulses can be used in two ways: (1) integration over time gives the model spectrum of that pulse and (2) integration over various energy bands gives model light curves of that pulse in those energy bands.

In our analysis, we first generate a two-parameter XSPEC table model using the guess values of $E_{\text{peak},0}$ and $\phi_0$ and then use this table model to determine the best-fit values of these two parameters by fitting the time-integrated spectrum (see Section 4.1.3). With this method, we get a complete description of the pulse with model parameters determined from the data. Using this model we can reconstruct the three-dimensional pulse model for the best-fit value over the whole procedure.

4.1.3. Specification of the Table Model and the Best-fit Values

For all the pulses, we use a time-grid resolution of 0.5 s and energy-grid resolution of 2.0 keV. Each pulse has a separate XSPEC table model, though the first and second pulses are combined together as the data overlap. A typical table model contains a spectrum in the 2–200 keV energy range for 200 values of $E_{\text{peak},0}$ from 100.0 keV to 1100.0 keV and 50 values of $\phi_0$ from 2.0 photon cm$^{-2}$ to 77.0 photon cm$^{-2}$, energy binning information, parameter values, and the required header keywords standardized as per the requirement by XSPEC described in OGIP Memo OGIP/92-009.

The additive table model is used to determine the best-fit values of $E_{\text{peak},0}$ and $\phi_0$ by the standard $\chi^2$ minimization procedure. The best-fit values with nominal 90% confidence errors are reported in Table 2. The parameters, $E_{\text{peak},0}$ and $\phi_0$ of the first two pulses are assumed to be the same. It should be noted here that we have used the normalization $A_n$ as a global parameter to calculate $\phi(t)$. The normalization of the subsequent pulse profile is derived from the integration of $f(E)$ over the total energy band (see Section 4.1.2). Effectively this leads to a spectrum with normalization as a free parameter. This normalization is determined during the spectral fitting using XSPEC, and is also reported in Table 2.

### Table 2

| Pulse | $E_{\text{peak},0}$ | $\phi_0$ | Norm | $\chi^2$ ( dof) | $t_1$ (s) | $t_2$ (s) | $t_3$ (s) |
|-------|---------------------|----------|------|----------------|----------|----------|----------|
| 1     | 359.65^55_92        | 12.2^2.5_1.1 | 0.74 ± 0.06 | 40.12 (75)     | 795.4^0.2_3      | 0.54^0.05_0.05 | 40.1^0.2_0.2 |
| 2     |                     |           |      |                | 858.2^0.6_4     | 0.58^0.04_0.05 | 44.2^0.2_0.8 |
| 3     | 324.82^88_83        | 18.8^0.6_6 | 0.54 ± 0.04 | 31.41 (75)     | 353.4^3.3_35    | 2.47^0.12_0.09 | 50.3^1.5_1.2 |
| 4     | 307.41^41_99        | 12.0^0.2_2 | 0.19 ± 0.04 | 56.42 (75)     | 532.0^0.09_32   | 1.58^0.15_0.16 | 81.0^2.5_3.4 |

Notes. The first two pulses are combined together. The other pulse characteristics ($t_1$, $t_2$, and $t_3$) are also reported.

The GRB light curve shows rapid time variable components over and above the smooth pulse structure. In the pulse description we consider only this smooth variation. Any small rapid time variability in the data gives large value of $\chi^2$ when we use the smooth pulse model for fitting. Hence, the normalization factor could not be determined by $\chi^2$ minimization. Instead, we physically examined the heights and determined the normalization. The co-added pulses reproduce the light curve quite well. Hence, we can conclude that the total light curve and the integrated spectrum, with the assumption of $E_{\text{peak}}(t)$ varying with $\phi(t)$ in a predetermined way (Equation (3)), correctly reproduces the energy-resolved light curves. This can be

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Figure 5. Three-dimensional model of the whole GRB using a model with the best-fit values of $E_{\text{peak},0}$ and $\phi_0$ for each pulse. Counts in arbitrary unit are plotted in the vertical axis against time and energy. The pulses are shifted to original pulse start time (see Table 2).

Figure 6. Observed light curve in the full energy range 15–200 keV fitted with Norris' exponential model is shown in the left panel. The timing parameters are determined and used in the pulse generation to predict light curves in all energy bands. One such predicted light curve in the 25–50 keV region is shown along with the observed light curve in the right panel. The count s$^{-1}$ in the y-axis is BAT mask weighted count s$^{-1}$.

taken as a confirmation of the assumption of the $E_{\text{peak}}$ variation. It should, however, be noted that a single joint spectral fit is done for pulses 1 and 2 and hence the derived values of $E_{\text{peak},0}$ and $\phi_0$ for the first two pulses are only the average values.

4.2.2. Derived Timing Parameters

The pulse width of individual pulses in the various energy bands can be derived by fitting the light curve using Equation (1) and using the best-fit values of $\tau_1$ and $\tau_2$ (see Section 3.2). For overlapping pulses this method is erroneous, e.g., the rising part of one pulse can fall on top of the falling part of the previous pulse thus affecting the width. Also, pulse delay characteristics are affected by these overlaps. In such cases the method described here is very useful. It takes as an input some global parameters ($A_n$, $\tau_1$, $\tau_2$, $\alpha$, and $\beta$) which are average quantities characterizing the pulse and some constant parameters ($E_{\text{peak},0}$, $\phi_0$), determines the variable parameter ($E_{\text{peak}}(t)$) over the time grids, and generates the three-dimensional model of the pulse. Note that the timing parameters $\tau_1$ and $\tau_2$ are determined from the energy integrated light curve and are fixed in our model. The timing properties of the pulse (e.g., width in various energy bands, spectral delay) are now determined crucially by the evolution of the peak energy. Integration of the three-dimensional model in various energy bands generates the light curves in those energy bands. Hence, physically we can determine the full width at the 1/e intensity and the peak positions. We define the spectral delay as the shift in the peak position at each energy band compared to the lowest energy band (15–25 keV).
The derived pulse width and delay are reported in Tables 3 and 4, respectively. In Table 3, the numbers in parentheses are the width determined from Norris’ exponential fitting for individual light curves. Figure 7 shows a comparison between the measured width following the new method with that determined by fitting the light curve. We note a systematic decrement of the width following the new method with that determined by fitting the entire light curve. We note that individual pulses rather than co-added pulses are taken into consideration. Hence, measured widths are more accurate and devoid of contamination effects from other pulses.

One of the pulse properties of GRB is broadening at lower energies (Norris et al. 1996; Hakkila & Preece 2011). Figure 8 (left panel) shows the pulse width variation with energy. While the first two pulses follow the normal trend, we note that the width for the third and fourth pulses broadens with higher energy. This cannot arise from the contamination of the previous pulse as could have been the argument for fitting the entire light curve. In our case, each pulse is generated and analyzed separately for the width determination. The energy–width plot of individual pulses is fitted with a linear model. The slopes are negative for the first two pulses ($(-9.4 \pm 1.7) \times 10^{-3}$ s keV$^{-1}$ and $(-11.8 \pm 2.4) \times 10^{-3}$ s keV$^{-1}$, respectively; $\chi^2 = 0.13$ (2) and 0.11 (2), respectively) and positive for the other two ($11.8 \pm 1.1) \times 10^{-3}$ s keV$^{-1}$ and $(14.2 \pm 10.6) \times 10^{-3}$ s keV$^{-1}$, respectively; $\chi^2 = 0.0046$ (2) and 0.0021 (2), respectively). Figure 8 (right panel) shows a comparison of the slopes measured by the linear fit of data determined by the two methods (compare slopes determined in Section 3.2). We note again that the slopes of the first two pulses are convincingly negative (low error bar), but slope of the other two pulses has large error bars. Hence, the evidence of reverse pulse broadening is tentative, though individual pulse analysis in the new method shows a better evidence for the reverse pulse broadening effect (see Figure 8, left panel).

This deviation from the canonical pulse width broadening with energy decrement may have a physical significance. In our analysis, the physical process of pulse emission is not considered. But phenomenologically, this occurs depending on the values of $\tau_1$ and $\tau_2$. A detailed comparison between the first pulse and the third pulse reveals the fact that they have different pulse width variation albeit having nearly similar parameters except for $\tau_1$ and $\tau_2$. These values are as follows (the numbers within parentheses are those of the third pulse): $\alpha = -1.11$ (−1.15), $\beta = -2.5$ (−2.5), $E_{peak,0} = 359$ (324), $\phi_0 = 12.2$ (18.8), $\tau_1 = 795.4$ (353.4), and $\tau_2 = 0.54$ (2.47). It is apparent that the main contributing factors for the different width–energy relation are the global values of $\tau_1$ and $\tau_2$. Hence, we examined for a generic pulse keeping all other parameters fixed at the values of the first pulse and varying $\tau_1$ for different values of $\tau_2$.

Figure 9 shows the regions in which pulse broadening or its reverse phenomenon can occur. This figure is generated by fixing all the parameters other than $\tau_1$ and $\tau_2$ to those for the first pulse. For four values of $\tau_2$ we vary $\tau_1$ and note the ratio of the width in 100–200 keV region ($w_4$) to that in the 15–25 keV ($w_1$) region. The solid line parallel to $\tau_1$ with $w_4/w_1 = 1$ divides the plot into two regions: (1) normal width broadening region for

| Pulse | Energy Channel | Mean Energy (keV) | Delay (s) |
|-------|---------------|------------------|-----------|
| 1     | 15–25 vs. 25–50 keV | 35.45            | -0.135±0.011 |
|       | 15–25 vs. 50–100 keV | 68.07            | -0.375±0.023 |
|       | 15–25 vs. 100–200 keV | 123.73           | -0.730±0.045 |
| 2     | 15–25 vs. 25–50 keV | 35.45            | -0.195±0.005 |
|       | 15–25 vs. 50–100 keV | 68.07            | -0.555±0.033 |
|       | 15–25 vs. 100–200 keV | 123.73           | -1.070±0.023 |
| 3     | 15–25 vs. 25–50 keV | 35.45            | -0.012±0.004 |
|       | 15–25 vs. 50–100 keV | 68.07            | -0.040±0.012 |
|       | 15–25 vs. 100–200 keV | 123.73           | -0.085±0.005 |
| 4     | 15–25 vs. 25–50 keV | 35.45            | -0.020±0.010 |
|       | 15–25 vs. 50–100 keV | 68.07            | -0.065±0.035 |
|       | 15–25 vs. 100–200 keV | 123.73           | -0.095±0.005 |

Note. Delay is calculated with respect to the 15–25 keV band (mean energy: 20.82 keV).
which $w_4 < w_1$ and (2) anomalous width broadening region for which $w_4 > w_1$. Global values of $\tau_1$ and $\tau_2$ falling in the $w_4 < w_1$ region will lead to normal pulse broadening (i.e., pulse broadens with lower energy) and vice versa. We identify from the figure that the $\tau_1$ and $\tau_2$ values (795.4 and 0.54, respectively) of the first pulse lie well within the region of normal width broadening. We also note that the values of $\tau_1$ and $\tau_2$ for the third pulse (353.4 and 2.47, respectively) lie within the region of anomalous width broadening despite the fact that the parameter values used, other than $\tau_1$ and $\tau_2$, are those of the first pulse. This shows how insensitive the pulse broadening effect is with all other parameters and crucially determined by the global values of $\tau_1$ and $\tau_2$.

Another pulse property is the hard-to-soft spectral evolution. In Figure 10, we have plotted the model-predicted delay as a function of energy (left panel). It can be seen that the spectral time delay always shows a decrement with energy. The hard X-ray always precedes the softer one. The values for the first three peaks can be compared with the observed delay given in Rao et al. (2011) and this is shown in the right panel of Figure 10. The time intervals taken by Rao et al. (2011) are $T_0$ to $T_0 + 50$ s, $T_0 + 50$ s to $T_0 + 77$ s, $T_0 + 77$ s to $T_0 + 100$ s, and $T_0 + 100$ s to $T_0 + 180$ s. Among these the first time bin contains the precursor burst which is not taken in our calculation. The first and second pulses are combined in the second time bin. The third pulse is covered in the third time bin. Data of the fourth pulse cannot be compared with the time bin as they differ by $\sim 55$ s (80 s in time bin as compared to $\sim 25$ s in pulse analysis). The deviation of the model-predicted delay from the observed delay can be explained by the fact that the delay in the second time bin ($T_0 + 50$ to $T_0 + 77$) is the combined effect of the first two pulses. The data for the third time bin agrees within error with the model-predicted delay. Also, the observed delays are calculated using the peak position measurement and cross correlation of the pulses, whereas model-predicted delays are calculated from the peak position measurement alone.

### 4.3. Correlations and the Bigger Picture

One of the important properties of the prompt emission is that the various measured quantities correlate with luminosity. Particularly, the peak energy of the $\nu F_{\nu}$ spectrum, $E_{\text{peak}}$, correlates with isotropic energy $E_{\text{iso}}$ (Amati et al. 2002) and also with the peak isotropic luminosity $L_{\text{iso}}$ (Yonetoku et al. 2004). Ghirlanda et al. (2004) showed that the correlation is tighter with collimation-corrected energy, $E_{\gamma}$. Schaefer (2007) used a set of 69 GRB samples (up till 2006 June 7) with measured redshift to calculate various correlations, viz., lag–luminosity ($\tau_{\text{lag}}$–$L$), variability–luminosity ($V$–$L$), $E_{\text{peak}}$–$L$, $E_{\text{peak}}$–$E_{\gamma}$, minimum-rise–luminosity ($\tau_{R\gamma}$–$L$), number-of-peaks–luminosity ($N_{\text{peak}}$–$L$) to get distance moduli for each. Weighted average of them gave the distance modulus ($\mu$) which is plotted against the measured redshift ($z$) extending the Hubble Diagram (HD) to $z \geq 6$. Therefore, these correlations can be used to standardize the GRB energy budget making GRBs a class of cosmic distance indicators. Also, these correlations might point to an underlying fundamental physical process (Yamazaki et al. 2004; Rees & Mészáros 2005; Xu et al. 2005; Firmani et al. 2005, 2006, 2007; Ghirlanda et al. 2006a,
In order to establish the reality of these correlations one must show that all of these correlations hold just as the same way within a single GRB as for a sample of many GRBs. Ghirlanda et al. (2010) showed for a set of GRBs that the time-resolved correlations of a single GRB are similar to the time-integrated correlations among different GRBs. In the present work, we have used the underlying pulse structure to investigate the correlations: $E_{\text{peak},0} - L_{\text{iso}}$, $E_{\text{peak},0} - E_{\gamma, \text{iso}}$, $\phi_{0} - L_{\text{iso}}$, and $\phi_{0} - E_{\gamma, \text{iso}}$ within the pulses of a single GRB.

The correlations are shown in Figure 11. The mean and $3\sigma$ scatter of $E_{\text{peak},0} - L_{\text{iso}}$ (top left panel) and $E_{\text{peak},0} - E_{\gamma, \text{iso}}$ (top right panel; Ghirlanda et al. 2010) are shown for reference. As expected, the $E_{\text{peak},0}$ values always lie above the mean of the $E_{\text{peak}}$ values. It seems that the correlations of $E_{\text{peak},0}$ with $L_{\text{iso}}$ and $E_{\gamma, \text{iso}}$ are rather tighter in our case, though with only three points we cannot draw any definite conclusions. While the parameter $E_{\text{peak},0}$ is a constant, $E_{\text{peak}}$ is an average quantity. Hence, we expect that $E_{\text{peak},0}$ provides a better pulse description than $E_{\text{peak}}$. This can be tested in future for correlations of $E_{\text{peak},0}$ rather than $E_{\text{peak}}$ with other quantities in different GRBs. But if the same correlations hold for different GRBs then we might conclude (1) the correlations are rather physical and not an outcome of the bias in sample selection and (2) in a single multi-peaked GRB each pulse is generated independently. We also note that the calculated $L_{\text{iso}}$ and $E_{\gamma, \text{iso}}$ are somewhat lower than those calculated by Ghirlanda et al. (2010). This must have come from the instrumental effect as noticed earlier. The normalization of BAT is always less than that of Fermi. This leads to a lower flux calculated from the BAT spectrum.

5. DISCUSSION AND CONCLUSIONS

We have attempted to explain the timing and spectral variations within a pulse of GRB by a simple empirical model and have given a prescription to measure the parameters of this model. We use simultaneous data from Swift/BAT and Fermi/GBM to determine the average pulse spectral characteristics using the Band model. Then we use the integrated light curve from Swift/BAT to get a simple description of the time evolution using Norris’ exponential model. Using these parameters, we develop a method to fit the spectrum using XSPEC table model by assuming that $E_{\text{peak}}(t)$ decreases exponentially with fluence in the pulse. We determine the parameters of the model and then find that these parameters can correctly describe the energy dependence of the pulse characteristics such as width and spectral lags. We also find, in the data, a tentative evidence of anomalous width broadening with energy for some pulses. The joint spectral and timing analysis developed here confirms this phenomena for the same pulses at least in the lower energy bands.

The method developed here is applicable for both single pulse and structured GRBs. Most of the long GRBs are structured which makes them difficult for pulse analysis. As far as the correlations are concerned, pulse analysis is more indicative than intensity-guided time-resolved spectroscopy. Hence to draw a conclusion regarding these correlations within a sample of GRBs and within the pulses of a single GRB, we must include these structured GRBs with multiple pulses. Kocevska et al. (2003) have prescribed a method for short, clean pulses. Our method extends the domain to all kinds of GRBs. Also the present method is much more physical than the time-resolved one in the sense that the individual pulses are treated separately. Hence, there will not be contamination effects. The $L_{\text{iso}} - E_{\text{peak},0}$ looks tighter because correlations within pulses may be more physical than the time-resolved correlation or the time-integrated correlations. In future, the method developed here can be used for a large set of GRBs (onto their individual pulses) to investigate the improvement in the correlations.

It is very interesting to note that the two distinct pulses (pulse 3 and pulse 4) in GRB 090618 have $E_{\text{iso}}$ values within a factor of two, but widely different $E_{\text{peak}}$ values (114 keV and 33 keV, respectively). They will show a huge scatter if used individually for a global correlation. The $E_{\text{peak},0}$ values, on the other hand, are closer to each other and lead to a lower scatter in the correlation (see Figure 11, top right panel). Hence, we suggest that the empirical relations are intrinsic to the emission mechanism of GRBs and $E_{\text{peak},0}$ values, instead of $E_{\text{peak}}$, should be the correct parameter to be used for correlation studies.
The method described in this paper is quite generic in the sense that any empirical description of the spectrum and its evolution with time can be tested against the data and the derived parameters can be used for global correlation studies. For example, the Band spectrum is derived from an extensive study of data from Compton Gamma Ray Observatory/BATSE, which is primarily sensitive above 50 keV (Band et al. 1993). Extension of the data to lower energies in fact requires additional features. For example, a time-resolved spectral study of GRB 041006 using HETE-2 data covering the energy range of 2–400 keV, indicated the presence of soft components, each of them having distinctive time evolution with time can be tested against the data and the derived parameters will have strong a bias of the bandwidth of the detectors, particularly for such low-resolution spectral data. Hence, a joint fitting of data with good overlap will result in a better estimate of the parameters.

In conclusion, we have developed a method to test empirical descriptions of the energy spectra and their evolution with time in GRBs and to derive the underlying physical parameters. This is the first attempt in this different approach to study various parameters and predict quantities like spectral delay and pulse width of individual pulses in a GRB.

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![Figure 11](image-url) Correlations between (a) $E_{\text{peak,0}} - L_{\text{iso}}$ (left panel, top); the dot-dashed line is the mean $E_{\text{peak}} - L_{\text{iso}}$ curve while the dashed lines represent 3σ scatter (from Ghirlanda et al. 2010), $\phi_{0} - L_{\text{iso}}$ (bottom); the dot-dashed line is the mean $\phi_{0} - L_{\text{iso}}$ line (from Kocevski et al. 2003) and (b) $E_{\text{peak,0}} - E_{\gamma,\text{iso}}$ (right panel, top); the dot-dashed line is the mean $E_{\text{peak}} - E_{\gamma,\text{iso}}$ curve while the dashed lines represent 3σ scatter (from Ghirlanda et al. 2010), $\phi_{0} - E_{\gamma,\text{iso}}$ (bottom).
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