DETECTION OF GRB 090618 WITH THE RT-2 EXPERIMENT ON BOARD THE CORONAS-PHOTON SATELLITE

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ABSTRACT

We present the results of an analysis of the prompt gamma-ray emission from GRB 090618 using the RT-2 Experiment on board the Coronas-Photon satellite. GRB 090618 shows multiple peaks, and a detailed study of the temporal structure as a function of energy is carried out. As the gamma-ray burst (GRB) was incident at an angle of 77° to the detector axis, we have generated appropriate response functions of the detectors to derive the spectrum of this GRB. We have augmented these results using the publicly available data from the Swift Burst Alert Telescope detector and show that a combined spectral analysis can measure the spectral parameters quite accurately. We also attempt a spectral and timing analysis of individual peaks and find evidence for a systematic change in the pulse emission characteristics for the successive pulses. In particular, we find that the peak energy of the spectrum, $E_p$, is found to monotonically decrease with time, for the successive pulses of this GRB.

Key words: gamma-ray burst: general – instrumentation: detectors – supernovae: general

1. INTRODUCTION

Gamma-ray bursts (GRBs) are very fascinating cosmic objects in the universe. Since their discovery in 1973 (Klebesadel et al. 1973), GRBs opened up a new domain of astrophysical research due to the rich observational characteristics of the afterglows in a vast range of electromagnetic spectrum from γ-rays to radio wavelengths (see Gehrels et al. 2009 for a review). There is general consensus in the literature that the diverse observational characteristics are due to the interaction of relativistic matter with the surrounding medium. The nature and energy source for this relativistic matter, particularly in the context of the long GRBs, could be in the nature of the bulk motion of ions (the Fireball Model—see, e.g., Piran 2004), cannon balls emitted from a compact object newly formed in a supernova explosion (Dar 2006), or particles accelerated by magnetized winds (the electromagnetic model—see Lyutikov 2006 and references therein). The long GRBs are associated with supernovae, and it is believed that relativistic matter of very high bulk Lorentz factor is generated in a conical jet during the collapse of a massive star at cosmological distances (see, for example, Meszaros 2002). The prompt gamma-ray emission has several characteristic correlations like the peak energy $E_p$ against the isotropic luminosity $E_{iso}$ (Amati et al. 2002), spectral lag against the peak luminosity (Norris et al. 2000), etc. (see Gehrels et al. 2009 for a summary of such correlations), and these relations are used even in predicting the redshift of long duration GRBs, although with a large uncertainty (close to a factor of two; see, for example, Xiao & Schaefer 2009). A detailed understanding of the prompt emission is necessary to put these correlations in a firm footing so that GRBs can be used as cosmological candles and also to have a clear understanding of the central engine and the basic jet/cannon-ball emission mechanism.

The morphology or temporal profile of the GRBs during the prompt emission varies asymmetrically with no apparent structure among the bursts. Some GRBs show multiple pulses and the individual pulses in a burst are separate and unique emission features with varying amplitude and intensity. In the framework of the Fireball Model (see Zhang 2007 and Meszaros 2002 for reviews), these pulses are created with different shock strengths at different locations of the jet. Observations suggest that in most of the bursts, an individual pulse profile is in the shape of fast-rise exponential decay (FRED), with the width decreasing with energy (Finimore et al. 1995; Norris et al. 2005). Spectral lag is another spectro-temporal property which is crucial to understand the dynamics and energetics of GRBs and can constrain the GRB models (Ioka & Nakamura 2001; Shen et al. 2005; Lu et al. 2006).

GRB 090618 is a very interesting object for several reasons. It is bright and relatively nearby (redshift ~0.5) making it a good candidate to expect to have a visible supernova (if it is like SN 1998bw—see Dado & Dar 2010), though no supernova has yet been associated with this GRB. Further, its intense hard X-ray and gamma-ray emission during the prompt phase enable one to make a time-resolved spectral analysis (see, for example, Ghirlanda et al. 2010). In this paper, we make a detailed analysis of the prompt emission in wide band X-ray and gamma-ray regions using data from the Swift Burst Alert Telescope (BAT) and the RT-2 Experiment on board the Coronas-Photon satellite (preliminary results are given in Rao et al. 2009). Since this is the first result from this experiment, we describe in detail the methodology used in deriving the response matrix and spectral fitting. We augment our results by using the publicly available Swift BAT data and make a combined spectral fit. We examine the spectral and temporal characteristics of the individual pulses during the prompt emission of this GRB and investigate the...
implications to the source emission mechanisms. In Section 2, a summary of observations on GRB 090618 is given, and in Section 3 a brief description of the RT-2 Experiment is given. Observations and analysis results (RT-2 and BAT data) are given in Section 4 and finally, in Section 5, a discussion of the results is presented along with relevant conclusions.

2. GRB 090618

The bright and long gamma-ray burst GRB 090618 was discovered with the Swift BAT on 2009 June 18 at 08:28:29 UT (Schady et al. 2009a, 2009b, 2009c) at a redshift of $z = 0.54$ (Cenko et al. 2009a). The GRB was detected by various observatories in X-ray and gamma-ray energies such as AGILE (Longo et al. 2009), Fermi Gamma-ray Burst Monitor (McBreen et al. 2009), Suzaku WAM (Kono et al. 2009), Konus-Wind on board the Wind satellite and Konus-RF on board the Coronas-Photon satellite (Golenetski et al. 2009), the RT-2 Experiment on board the Coronas-Photon satellite (Rao et al. 2009), etc. The optical afterglow of GRB 090618 was soon detected with the Katzman Automatic Imaging Telescope (KAIT; Perley et al. 2009), ROTSE-IIIb (Rujopakarn et al. 2009), Palomar 60 inch telescope (Cenko et al. 2009b), and various other optical, infrared, and radio observatories.

The X-ray afterglow of GRB 090618, as measured by the Swift X-ray Telescope (XRT; Schady et al. 2009c), was very bright in X-rays, initially. Soon after, the flux decayed rapidly with a slope of $\sim 6$ before breaking at $T_0 + 310$ s ($T_0 = 08:28:29$ UT) to a shallower slope of $0.71 \pm 0.02$ (Beardmore et al. 2009). Further breaks at longer timescales were also reported (Schady et al. 2009c). Spectral fitting to the Swift data in the range of $T_0 + 250$ to $T_0 + 1065$ s with a power-law model modified by interstellar absorption yielded a photon index of $\sim 2$ and the intrinsic absorption of $1.78 \times 10^{21}$ cm$^{-2}$ (Beardmore et al. 2009). They estimated the 0.3–10 keV unabsorbed flux to be $1.16 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$.

Significant spectral evolution was observed during the prompt emission of the burst. Time-averaged spectrum from $T_0 - 4.4$ to $T_0 + 213.6$ s was well fitted by a power law with an exponential cutoff with the photon index of 1.42 and $E_p$ of 134 keV (Sakamoto et al. 2009). Time-integrated 20 keV–2 MeV spectra obtained from the Konus-Wind (from $T_0$ to $T_0 + 242$ s; $T_0 = 08:28:24.974$ UT) on board the Wind satellite and the Konus-RF (from $T_0$ to $T_0 + 242$ s; $T_0 = 08:28:27.060$ UT) instrument on board the Coronas-Photon satellite, when fitted by the GRB (band) model, provided the values of the low-energy photon index ($\alpha$), high-energy photon index ($\beta$), and peak energy ($E_p$) as $-1.28$, $-2.66$, and 186 keV (for Konus-Wind), and $-1.28$, $-3.06$, and 220 keV (for Konus-RF), respectively (Golenetski et al. 2009). The BAT light curve of the GRB was found to be of a multi-peak structure with a duration of about 130 s. The time-averaged BAT spectrum from $T_0 - 5$ to $T_0 + 109$ s can be described by simple power-law model with index $\sim 1.7$ (Baumgartner et al. 2009). The fluence in the 15–150 keV band is $1.06 \pm 0.01 \times 10^{-4}$ erg cm$^{-2}$. The multi-peak profile was also seen in the 50 keV–5 MeV range light curve obtained from the Suzaku Wide-band All-sky Monitor (Kono et al. 2009).

Ukwatta et al. (2010) derived the spectral lag of this GRB using the Swift BAT data and found that it supports the existence of a lag-luminosity relation. Ghirlanda et al. (2010) investigated the time-resolved spectral characteristics of several GRBs using Fermi data and concluded that the $E_p - L_{iso}$ relation holds well during the rising and decaying phases of pulses for a few GRBs, particularly for GRB 090618.

3. RT-2 EXPERIMENT ON BOARD THE CORONAS-PHOTON SATELLITE

The RT-2 Experiment (RT—Roentgen Telescope), which is a part of the Indo-Russian collaborative project of the Coronas-Photon mission (Kotov et al. 2008; Nandi et al. 2009), is designed and developed for the study of solar hard X-rays in the $\sim$15–100 keV energy range. This experiment consists of three instruments (two phoswich detectors called RT-2/S and RT-2/G, and one solid-state imaging detector RT-2/CZT) and one processing electronic device (RT-2/E). The RT-2/S and RT-2/G detector assembly consisting of NaI(Tl)/CsI(Na) scintillators in phoswich assembly viewed by a photomultiplier tube (PMT). Both the detector assemblies sit behind respective mechanical slat collimators surrounded by a uniform shield of tantalum material and having different viewing angles of $4^\circ \times 4^\circ$ (RT-2/S) and $6^\circ \times 6^\circ$ (RT-2/G). The RT-2/S covers $\sim 15$ to 100 keV, extendable up to 1 MeV, whereas the use of an aluminum (Al) filter in RT-2/G sets the lower threshold at $\sim 20$ keV. The RT-2/CZT consists of three CZT detector modules (OMS40G256) and one CMOS detector (RadEye-1) arranged in a 2 x 2 array. Each CZT module consists of 256 individual detectors (pixel dimension of 2.5 mm x 2.5 mm), which are controlled by two ASICs. The CMOS detector consists of 512 × 512 pixels of individual pixel dimension of 48 μm. The entire CZT–CMOS detector assembly is mounted behind a collimator with two different types of coding devices, namely coded aperture mask (CAM) and Fresnel zone plate (FZP), surrounded by a uniform shield of tantalum material and has varying viewing angles of $6^\circ$–$6^\circ$ depending on different configurations of the collimator (Nandi et al. 2010). The RT-2/CZT payload is the only imaging device in the Coronas-Photon mission to image the solar flares in hard X-rays in the energy range of 20–150 keV. All three-detector systems are interfaced with the satellite system (called SSRNI) through the RT-2 Electronic processing payload (RT-2/E). The RT-2/E receives necessary commands from the satellite system and passes it to the individual detector system for proper functionality of the detector units and acquires data from the detector system and stores these in its memory for further processing.

The mission was successfully launched from Plesetsk Cosmodrome, Russia on 2009 January 30. To maximize the Sun observation time, the satellite was put into a low earth (500 km) Sun-synchronous near-polar (inclination 82°) orbit. The test and evaluation results of this payload are described in Debnath et al. (2010), Kotoch et al. (2010), Nandi et al. (2010), Sarkar et al. (2010), and Sreekumar et al. (2010). Some details of the experiment can also be found at http://csp.res.in/rt2-main.html.

4. OBSERVATION AND ANALYSIS

4.1. RT-2 Observations

During the GRB event, the RT-2 payload was completely in the “SHADOW” mode (away from the Sun) which started at 08:16:10.207 UT and ended at 08:37:35.465 UT. GRB 090618 was detected by the RT-2 instruments (Rao et al. 2009) with a large off-axis angle of 77°. Data from RT-2/S and RT-2/G are used for the present analysis. The scientific data from the detectors were stored in the memory of RT-2/E and then compressed using the on board software before being transferred to the satellite system (known as SSRNI) for a down-link to the ground station. During the “SHADOW” mode, the spectra are accumulated every 100 s (see the spectral analysis
section) and eight channel count rates (for each detector) are accumulated every 1 s. These eight channels are divided equally between the 15–100 keV data from the 3 mm thick NaI (TI) detector and the 26–1000 keV data from the 25 mm thick CsI (Na) detector, operated in phoswich mode. For the present work, we use the latter four channel data, which have the ranges of 26–59 keV, 59–215 keV, 215–330 keV, and 330–1000 keV, respectively.

The “SHADOW” mode data of the RT-2/S and RT-2/G detectors of “GOOd” time span (away from high background regions) of ∼800 s from 08:23:27 to 08:36:47 UT were analyzed. During this time, the satellite was completely away from both the polar cap and high background South Atlantic Anomaly regions. GRB 090618 was detected by both the scintillator detectors. The light curves of 1 s time resolution were generated from the data obtained from both the detectors at different energy bands. Spectral data of 100 s, during the present GRB event, were also analyzed to study the evolution of the GRB spectrum.

4.2. Swift BAT Observations

BAT (Barthelmy et al. 2005) on board the Swift mission (Gehrels et al. 2004) is a highly sensitive, large field of view instrument, primarily designed to monitor the sky to detect gamma-ray events. It consists of an array of CdZnTe detectors, located behind a CAM. Swift also has an XRT (Burrows et al. 2005) and a UV/Optical Telescope (UVOT; Roming et al. 2005) which can make follow-up observations within a few hundred seconds after the trigger.

BAT registered GRB 090618, triggered at 08:28:29 UT. The BAT position of the burst with 3 uncertainty is R.A.(J2000), decl.(J2000) = 294.021, +78.353 (Schady et al. 2009a). The astrometrically corrected position using Swift-XRT data and Swift-UVOT data is R.A.(J2000), decl.(J2000) = 293.99465, +78.35677 (Evans et al. 2009; Schady et al. 2009c). We have analyzed the Swift BAT data to understand the prompt emission from this GRB.

We used heasoft6.5.1 for our analysis. First, we created the detector plane image using the task batbinev and then the detector mask file was created using task bdatetmask. The quality map file was created using task bathotpix. Mask weighting using new XRT and UVOT position to BAT data was applied using task batmaskwrtv. Then, mask-weighted light curves were generated using task batbinev. The GRB light curve shows multi-peaked structure with a precursor and the main burst starts at $T_0 + 50$ s. We generated light curves for the full burst ($T_0$ to $T_0 + 180$) in four energy bands: 15–25 keV, 25–50 keV, 50–100 keV, and 100–200 keV (these are the energy ranges used in Ukwatta et al. 2010, for timing analysis).

4.3. Timing Analysis

The GRB was detected in the wide band of 26–1000 keV with both the RT-2 detectors. Since the GRB is incident at a large incident angle, meaningful light curves were available from the CsI (TI) detectors in different energy bands (26–59 keV, 59–215 keV, and 215–1000 keV ranges for RT-2/S, and 26–59 keV, 59–215 keV, 215–330 keV, and 330–1000 keV ranges for RT-2/G). The light curves, obtained from RT-2 and BAT instruments, are shown in Figure 1 with a bin time of 1 s and the time is given with respect to the BAT trigger time $T_0 + 50$ s. The other two weak emissions are registered at $T_0 + 85$ and $T_0 + 115$ s with low intensity. Another instrument, the Konus-RF on board the Coronas-Photon satellite, also detected GRB 090618 with an identical burst profile (Golenetskii et al. 2009). The burst profile is not clearly detected in the lowest energy band of RT-2 (26–59 keV), whereas in the high-energy X-rays, the burst is detected with significant emission. There is a very significant softening of the spectrum in the precursor with the 25–50 keV light curve peaking several seconds after the high-energy light curves. The main pulse at $T_0 + 65$ s shows a double structure, the 50–100 keV BAT profile showing a close similarity to the 59–215 keV RT-2 light curve. The pulse at $T_0 + 85$ s shows a single smooth structure in 100–200 keV (similar to the 59–215 keV RT-2 light curve), with an indication of multiple structures in the low energies.

We have attempted to model the pulse with the FRED profile developed by Kocevski et al. (2003). The empirical relation for the flux (photons counts s$^{-1}$) distribution is given by

$$F(t) = F_m \left( \frac{t}{t_m} \right)^r \left[ \frac{d}{d+r} + \frac{r}{d+r} \left( \frac{t}{t_m} \right)^{-(r+1)/(r+1)} \right]^{-(r+1)/(r+1)}, \quad (1)$$

where $F_m$ is the maximum flux at $t_m$, and $r$ and $d$ are the rising and decaying indices, respectively. First, we fit the total light curves (26–1000 keV for RT-2 and 15–200 keV for BAT). The start times for fitting (for each pulse) were kept fixed at

![Figure 1](link-to-figure)
curves with burst profiles are shown in Figure 2 for the total energy band of 26–1000 keV for the RT-2 detector (top panel). The fitting procedure is repeated for light curves of different energies. The times of the maximum emission \( t_m \) were varied between 15 s and 25 s. Since there were negligible changes in the derived parameters, particularly for the measurement of width, we kept \( t_m \) fixed at 25 s. The reduced \( \chi^2 \) for the RT-2 data is 1.38, for 75 degrees of freedom (dof). For the higher sensitivity BAT data, however, the FRED profile does not take into account the sub-structures in the pulses, and hence formally unacceptable fits (reduced \( \chi^2 \gg 10 \)) were obtained. Since our main emphasis is to find the broad pulse characteristics, we give below the parameters obtained from a FRED fitting. Furthermore, we find that the derived parameters for pulses 1 and 2 from the BAT data (these two pulses have a large overlap) are quite sensitive to the initial parameters used for fitting and hence the quoted formal errors could be underestimates.

The resultant derived parameters, along with the nominal 1\( \sigma \) errors (obtained from the criterion \( \Delta \chi^2 = 2.7 \)), are given in Table 1. There is reasonable agreement in the derived parameters, obtained from RT-2 and BAT data. While fitting, an upper bound of 1000 is kept for the parameter \( d \) (for \( d \gg r \), F(t) becomes independent of \( d \)). We have measured the pulse width as the FWHM value of the fitted light curve. The fitted light curves with burst profiles are shown in Figure 2 for the total energy band of 26–1000 keV for the RT-2 detectors (bottom panel) and for the total energy band of 15–200 keV for the BAT detector (top panel). The fitting procedure is repeated for light curves of different energies. The times of the maximum emission \( t_m \), however, were kept fixed at those values obtained from the fitting for the full energy light curves of the respective detectors (RT-2 and BAT). The value of \( t_m \) could depend on energy up to about a second for these energies (see the delay analysis presented later), which might result in a further systematic error in the width measurement of \( \pm 1 \) s. We have plotted the width as a function of mean energy in Figure 3. Mean energies are calculated as the mean energy of incident photons in the detector, based on the response function of the detectors, and they are derived to be 125.62 keV, 266.6 keV, and 427.5 keV for the 59–215 keV, 215–330 keV, and 330–1000 keV bands, respectively, for the RT-2 data. The mean energies for the four energy bands of BAT data are 20.82 keV, 35.45 keV, 68.07 keV, and 123.73 keV, respectively.

The first two pulses have similar profiles in both data sets, though in the RT-2 data the first pulse is much stronger than the second one. There is an indication of further sub-structures in the BAT data which is not very apparent in the RT-2 data, possibly due to the lower sensitivity. The width decreased monotonically with energy. Also, there is a steepening trend for the latter pulses, particularly for the third pulse. For example, by defining a width index \( \xi \) such that width \( \propto E^{-\xi} \) (Fenimore et al. 1995), we find \( \xi \)

| Pulse | Energy Range (keV) | \( t_m \) (s) | \( t_m \) (s) | \( r \) | \( d \) | Width (s) |
|-------|-------------------|--------------|--------------|-------|-------|-----------|
| 1     | 26–1000 (RT-2)    | 8.7 ± 0.8    | 64.8 ± 0.2   | 27 ± 4 | 15 ± 5 | 3.9 ± 0.3 |
| 2     | 59–215 (RT-2)     | 5.9 ± 0.7    | 70.5 ± 0.3   | 8 ± 1  | 1000  | 7.2 ± 1.1 |
| 3     | 215–330 (RT-2)    | 3.3 ± 0.1    | 84.4 ± 0.2   | 6 ± 1  | 7 ± 1  | 13.4 ± 0.5 |
| 4     | 330–1000 (RT-2)   | 0.85 ± 0.14  | 114.1 ± 1.0  | 13 ± 6 | 5 ± 2  | 9.7 ± 0.6 |
| 1     | 26–1000 (BAT)     | 4.4 ± 0.3    | 64.8 ± 25    | 20 ± 5 | 3.7 ± 0.1 |
| 2     | 59–215 (BAT)      | 4.0 ± 0.2    | 70.5 ± 8     | 1000   | 7.2 ± 0.6 |
| 3     | 215–330 (BAT)     | 2.3 ± 0.1    | 84.4 ± 6     | 7 ± 1  | 13.5 ± 0.5 |
| 4     | 330–1000 (BAT)    | 0.6 ± 0.1    | 114.1 ± 8    | 5 ± 2  | 12.7 ± 1.0 |
| 1     | 15–200 (BAT)      | 1.51 ± 0.21  | 64.8 ± 32    | 12 ± 1 | 3.9 ± 0.6 |
| 2     | 15–25 (BAT)       | 0.36 ± 0.22  | 70.5 ± 15    | 1000   | 4.0 ± 3.9 |
| 1     | 25–50 (BAT)       | 2.80 ± 0.03  | 65.0 ± 13.6  | 39 ± 4 | 5.0 ± 0.1 |
| 2     | 50–100 (BAT)      | 4.31 ± 0.03  | 70.5 ± 7.0   | 1000   | 8.0 ± 0.1 |
| 3     | 100–200 (BAT)     | 3.36 ± 0.02  | 84.4 ± 5.1   | 5.4 ± 0.1 | 15.9 ± 0.1 |
| 4     | 100–200 (BAT)     | 1.41 ± 0.01  | 114.3 ± 8.5  | 3.4 ± 0.1 | 14.5 ± 0.1 |

Note: \( \xi \) is such that width \( \propto E^{-\xi} \).
respectively. We have used the utility crosscor of the XRONOS to be 0.18, 0.07, 0.14, and 0.05, respectively, for the four pulses, for a combined fit to the RT-2 and BAT data. These parameters are summarized in Table 3.

To investigate the softening of the spectra, we have performed cross-correlation analysis between the light curves of various energies using the BAT data. We have taken the 15–25 keV range as the base energy. Cross-correlation is done for the full light energies using the BAT data. We have taken the 15–25 keV range consisting of four FRED profiles each. See Table 1 for the model parameters.

### Table 2

| Division No. | Energy Bands | Mean Energy (keV) | Time Lag (s) |
|--------------|--------------|------------------|-------------|
| Part 1 ($T_0$ to $T_0 + 50$) | 15–25 vs. 25–50 keV | 35.45 | –2.0 ± 0.07 |
| | 15–25 vs. 50–100 keV | 68.07 | –3.85 ± 0.10 |
| | 15–25 vs. 100–200 keV | 123.73 | –7.00 ± 0.14 |
| Part 2 ($T_0 + 50$ to $T_0 + 77$) | 15–25 vs. 25–50 keV | 35.45 | –0.424 ± 0.026 |
| | 15–25 vs. 50–100 keV | 68.07 | –0.721 ± 0.030 |
| | 15–25 vs. 100–200 keV | 123.73 | –1.050 ± 0.035 |
| Part 3 ($T_0 + 77$ to $T_0 + 100$) | 15–25 vs. 25–50 keV | 35.45 | –0.070 ± 0.04 |
| | 15–25 vs. 50–100 keV | 68.07 | –0.010 ± 0.03 |
| | 15–25 vs. 100–200 keV | 123.73 | –0.210 ± 0.033 |
| Part 4 ($T_0 + 100$ to $T_0 + 180$) | 15–25 vs. 25–50 keV | 35.45 | –0.655 ± 0.030 |
| | 15–25 vs. 50–100 keV | 68.07 | –1.349 ± 0.040 |
| | 15–25 vs. 100–200 keV | 123.73 | –1.775 ± 0.052 |
| Total ($T_0$ to $T_0 + 180$) | 15–25 vs. 25–50 keV | 35.45 | –0.495 ± 0.026 |
| | 15–25 vs. 50–100 keV | 68.07 | –0.872 ± 0.028 |
| | 15–25 vs. 100–200 keV | 123.73 | –1.310 ± 0.035 |

software package (a part of the HEASOFT software package of HEASARC) to derive the cross-correlation function (CCF) with respect to lag. A Gaussian function was used to fit the CCF and measure the time lag, and the error is estimated using the criteria $\Delta \chi^2 = 4.0$ (see Dasgupta & Rao 2006). The results of the cross-correlation analysis are given in Table 2. We found soft lags which show clear energy dependence. The measured lag increases with energy and they are shown in Figure 4. There is also a tendency for this steepening to be flatter for the latter pulses. Defining a delay index $\xi$ such that delay $= a + d_i \ln(E)$, where $a$ is a constant, we find $d_i$ to be very steep for the precursor ($–3.71$) and it increased from $–0.50$ for second part (pulses 1 and 2) to $–0.13$ for third part (pulse 3). For the fourth part (pulse 4), however, $d_i$ is found to be $–0.92$. The values of $\xi$ and delay index ($d_i$) are compiled in Table 3.

Ukwatta et al. (2010) have derived delays for the light curve of $T_0 + 46.01$ to $T_0 + 135.35$ s as $–0.171$, $–0.314$, and $–0.579$ s, respectively, in three energy bands given in Table 3, which are close to the average values of delays for second and third parts ($T_0 + 50$ to $T_0 + 100$ s) reported in Table 3 ($–0.247$, $–0.365$, $–0.495$, $–0.872$, and $–1.310$ s).

![Figure 2](image1.png)

**Figure 2.** Light curves of GRB 090618 obtained from Swift BAT and the RT-2 experiments for the respective full energy ranges, shown along with a model consisting of four FRED profiles each. See Table 1 for the model parameters.

![Figure 3](image2.png)

**Figure 3.** Pulse width variation as a function of average energy. For the four pulses (1 to 4; see the text), data are plotted as filled circles, filled squares, filled triangles, and circles with plus signs, respectively, for the BAT data and open circles, open squares, open triangles, and circles, respectively, for the RT-2/G data.
We get consistent results in the time span used in their work.

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we get consistent results in the time span used in their work.

4.4. Spectral Analysis

We have analyzed the spectral data during the GRB event. 

It showed the typical band spectrum with peak energy at 

about 164 keV and integrated 20 keV–1 MeV fluence of 

2.8 × 10−4 erg cm−2. We used 15–200 keV BAT data and 

the 100–650 keV RT–2 data of the GRB 090618 to perform 

joint spectral fitting.

The spectral information was available in the RT–2 data every 

100 s. The output from each detector is passed through two 

amplifiers of different gains (G1 and G2) and spectral data were 

available for each of the amplifiers: 1024 channel spectra for G1 

(covering the energy range of 26–215 keV for the CsI detector) 

and 256 channel spectra for G2 (covering the energy range of 

215–1000 keV). The number of channels are suitably rebinned 

for the spectral fitting.

The RT–2/S and RT–2/G detectors are essentially collimated 

phoswich detectors user for solar flare studies (Debnath et al. 

2010). The shielding used for these detectors, however, are op- 

timized to use them for hard X-ray spectroscopic studies of solar 

flares in the 15–100 keV region and as omni-directional hard 

X-ray/gamma-ray detectors between ∼50 keV and 1000 keV

and −2.80±0.2 (Pulse 4).

Part 2

−1.23 ± 0.05 < −2.1 322±70 54 56/55 248±65 55 0.18 ± 0.03 and −0.50 (Pulses 1 and 2)

Part 3

−1.39 ± 0.03 < −2.4 ± 0.2 211±20 11 55/55 129±13 13 0.14 ± 0.02 −0.13 (Pulse 3)

Part 4

−1.70±0.10 < −2.80±0.2 111±20 14 37/55 33±15 14 0.05 ± 0.01 −0.92 (Pulse 4)

Table 3

Best-fit Spectral Parameters from a Combined Fit to BAT and RT–2 Spectra Along with Timing Parameters

| Part       | α     | β     | Eν (keV) | χ²/dof | Eγ (keV) | ξ     | δt (s) |
|------------|-------|-------|---------|--------|---------|-------|--------|
| Full       | −1.40 ± 0.02 | −2.5±0.3 | 273 ± 31 | 56/101 | 164 ± 24 | ...   | −0.64  |
| Part 1     | −1.18±0.13 | < −1.6 | 322±70 | 54/55 | 264±205 | ...   | −3.71  |
| (Precursor)|       |       |         |        |         |       |        |
| Part 2     | −1.23 ± 0.05 | < −2.1 | 322±70 | 54/55 | 248±65  | 55    | 0.18 ± 0.03 and −0.50 |
| (Pulses 1 and 2)| | | | | | | |
| Part 3     | −1.39 ± 0.03 | < −2.4 ± 0.2 | 211±20 | 11 | 129±13 | 13 | 0.14 ± 0.02 −0.13 |
| (Pulse 3)  |       |       |         |        |         |       |        |
| Part 4     | −1.70±0.10 | < −2.80±0.2 | 111±20 | 14 | 33±15  | 14 | 0.05 ± 0.01 −0.92 |
| (Pulse 4)  |       |       |         |        |         |       |        |

Figure 4. Measured delay of light curves with mean energy, E, with respect to the 15–25 keV light curve, plotted against E from the Swift BAT data. Data for the four parts (see the text) and the total light curve are shown as filled circles, filled squares, filled triangles, circles with plus sign, and stars, respectively.

Figure 5. Effective area of RT–2 NaI(Tl) and CsI(Na) detectors, from an MC simulation for the GRB incident at an angle of 77°.

(Sarkar et al. 2010). GRB 090618 is incident at an angle of 77°, and we have used a Monte Carlo (MC) simulation technique using the GEANT4 toolkit to derive the spectral response of the RT–2 detectors for this large incident angle (see Sarkar et al. 2010 for details). We created a mass model of the detector including all parameters like detector sizes, collimator, shield materials, and mechanical support structures. Incident photons are used for the simulation in the energy range of 1–1000 keV in 50 equal bins in log scale and 10⁵ photons in each bin are considered. The number of photons registered in the detectors as a function of energy is normalized to the incident photons for a GRB model with the spectral parameters of α = −0.32, β = −5.0, and E₀ = 67.7 keV. The results are insensitive to model parameters (see later). This normalization is deemed as the effective area of the detectors. The derived effective areas for the NaI and CsI detectors are shown in Figure 5. Since the effective area of CsI is about an order of magnitude larger than the NaI detector, we have taken only the CsI data (and the corresponding response function) for our spectral fitting. The response matrix for the RT–2 detectors are generated using the genresp tool of ftools. The channel–energy conversion is derived from the background spectral line at ∼58.0 keV (Nandi et al. 2009) and 122 keV line due to the on-board calibration source (Co57) and the energy resolution function is taken from the ground calibrations. Using this response matrix, a joint fit to the RT–2 and BAT data is performed. From the derived best-fit spectral parameters, MC simulation is again carried out and the RT–2 response matrix is again created.
Convergent results were obtained in the first trial itself, indicating that direct blocking from the surrounding material and interaction with detector play a major part of the response and the second-order effects like scattering are unimportant for response matrix generation, at least to the level of sensitivity achieved for GRB 090618.

Except for a 2 mm aluminum filter in RT-2/G, both the detectors are identical in performance. The setting for deriving the on board counts in the high-energy channels is lower in RT-2/S and hence we have a single energy bin above 215 keV in RT-2/S (compared to the two energy bins in RT-2/G). Though we get consistent spectral results for both the detectors, we report the spectral parameters derived from RT-2/S which has better spectral response above 100 keV. While making a simultaneous fit to the BAT data, we kept the relative area between RT-2 and BAT as a free parameter, and it is derived to be 1.30 for the combined fit to the full data. The relative area between RT-2 G1 and G2, however, is kept fixed at what is dictated by the response matrix. For the time-resolved spectral fit, the relative area between RT-2 and BAT is kept fixed at the value obtained for the full data (i.e., 1.30).

The spectrum can be well fitted with the model introduced by Band et al. (1993). In this model, two power laws are smoothly joined at $(\alpha - \beta)E_0$, where $\alpha$ is the first power-law index, $\beta$ is the second power-law index, and $E_0$ is the break energy. The best-fit spectral parameters are given in Table 3, along with the calculated peak energy $E_p(= E_0(2 + \alpha))$, the best fit $\chi^2$, and the degrees of freedom used for the fitting. Figure 6 shows the best-fit model along with the unfolded spectrum. We divided the BAT data into four parts and for each part we perform the spectral analysis. Since RT-2 does not have time-resolved spectral data, we have used the count rates as broad spectral data for this time-resolved spectral analysis. The results are shown in Table 3. Timing analysis parameters (width index $\xi$ and delay index $d_\xi$) are also given in Table 3. We note that the spectral results agree quite well with that obtained from the Fermi data (Ghirlanda et al. 2010). The values of $E_p$, derived in this work, are 264 keV, 248 keV, 129 keV, and 33 keV, respectively, for the four parts which compares well with the value of 296 keV, 319 keV, 180 keV, and 81 keV derived for the peak of the light curves in these regions in the Fermi data (time ranges, after $T_0$, of 3–14 s, 63–67 s, 80–85 s, and 114–130 s, respectively).

Figure 6. Unfolded spectrum (in energy units) of GRB 090618 using Swift BAT and RT-2 data is shown along with the best-fit model. The residuals are given in the bottom panel.
redshift of 0.54 and the measured integrated fluence in the energy range of 20 keV–1 MeV of $2.8 \times 10^{-4}$ erg cm$^{-2}$, we calculate $E_{\text{iso}}$ to be $2.21 \times 10^{53}$ erg (beaming effects are neglected). The measured time-averaged peak energy ($E_{p,i}$) for the entire burst is around 164 keV, which gives the intrinsic peak energy ($E_{p,i}$) of 252 keV. Based on the measured values of $E_{p,i}$ and $E_{\text{iso}}$, it is found that the GRB 090618 closely follows the “Amati” relation with a minor deviation, which is within the 2$\sigma$ scatter. Hence, it could be concluded that GRB 090618 is a standard candle for the category of long duration GRBs along with various intrinsic properties that are discussed in this paper.

The recent detection of polarization in GRB 090102 (Steele et al. 2009) indicates the presence of ordered magnetic field in the source of GRBs during the prompt emission. The present measurement of the spectral and temporal parameters of GRB 090618 shows that the individual pulses show distinct behaviors.

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