Analysis of the Prompt Optical Emission of the Naked-Eye GRB 080319B

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Abstract. We present the observed/intrinsic optical parameters and the variability analysis of the Naked-Eye Burst, GRB 080319B, observed by the TORTORA wide-field optical monitoring system. The event is extreme not only in observed properties but also intrinsically: it is the most luminous event ever recorded at optical wavelengths. The temporal properties suggest short-lived periodic activities of the internal engine. This is the fastest optically variable source detected at cosmological distances.

Keywords: γ-ray burst, ground-based observations, time variability.

PACS: 98.70.Rz; 95.55.Cs; 95.75.Wx.

INTRODUCTION TO THE PHENOMENON: PROMPT OPTICAL EMISSION

Over the past nine years the prompt optical emissions contemporaneous with the γ-ray-active phase of a GRB have become subject of exciting debate in the astronomical community; the brevity of these phenomena and their fleeting nature makes them elusive and difficult to study. Due to the relative short duration of the prompt γ-ray emission (T ~ 0.2-100 sec) simultaneous follow-up observations at optical wavelengths suffer lack of rapid and precise burst localization. GRB 990123 was the first event for which optical emission was detected during the burst phase [1].

Nowadays, the fast and accurate localization of GRBs by the Swift mission [2] and its capability to alert fast-slewing robotic telescopes within few seconds after the burst has allowed to significantly increase the numbers of the events that are optically observed during the bursting phase, although the prompt optical emissions are usually not well sampled.

During the last years, we have investigated different search strategies in ultra fast photometry fields to measure rapid changes in light intensity in a phenomenon occurring within an extremely short period of time and randomly distributed over the sky [3, 4]. The high-speed and wide-field FAVOR [5] and TORTORA cameras represent the more recent developments in our search program in which intensified CCD imaging are employed and tested. In particular the ground-based TORTORA observations synchronized with the γ-ray telescope on board of the Swift satellite (BAT: Burst Alert Telescope) has permitted to trace the optical burst time structure of the GRB 080319B with unprecedented level of accuracy.

At the beginning of the May 2006 TORTORA was installed in the dome of the REM telescope located at ESO-La Silla Observatory (Chile) and successfully achieved its First Light [6].

OBSERVATION AND DATA REDUCTION

Observation

On 19 March 2008 at 06:12:49 UT (hereafter \( t_0 \)) the Swift’s Burst Alert Telescope triggered and located GRB 080319B (trigger = 306757; [7]) with a ~ 3’ radius error box. The bright burst was simultaneously detected by the Konus-Wind (KW) satellite [8] yielding a burst fluence of \( S_\gamma = 6.23 \pm 0.13 \times 10^{-4} \text{erg cm}^{-2} [20 \text{keV to 7 MeV}] \).

Assuming \( z = 0.937 \) [9] and the standard cosmology model \( (H_0 = 71 \text{ Km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.27 \text{ and } \Omega_\Lambda = 0.73) \) the isotropic energy release is \( E_{iso} = 1.30 \times 10^{54} \text{erg} \).

The field of the GRB 080319B was imaged before the GRB event by three independently ground-based optical sky monitoring. No optical precursors were detected in TORTORA, "Pi of the Sky" and RAPTOR surveys with observations starting 26 minutes, 16 seconds and 30 minutes before the Swift/BAT trigger, respectively. In RAPTOR [10] and "Pi of the Sky" [11] the first image with detectable optical emission started at \( t_0 = 1.87 \pm 5 \text{ sec} \) and...
at $t_0 = 2.75 \pm 5$ sec after the BAT trigger, respectively, when the optical counterpart became brighter than $V \approx 10^m$. In the TORTORA high temporal resolution dataset (0.13 sec exposure time), the first frame in which we detected the optical flux started at $t_0 = 9.18 \pm 0.065$ sec after the BAT trigger when the source became brighter than $V \approx 8^m$ [2]. The bright visual peaks which occurred during the prompt $\gamma$-ray emission approximately reached $V \approx 5.5^m$, this made it visible with naked eye in the BOOTES constellation [1] for $\sim 40$ seconds, assuming an observer in a dark location.

Since 05:46:22 UT REM telescope had observed the box of previous burst, GRB 080319A. At 06:12:49 UT, Naked-Eye Burst, GRB 080319B, flashed at $\sim 90$ degrees from the former, near the edge of TORTORA’s field of view. At 06:13:13 UT, REM started automatic repointing, and from 06:13:20 UT the burst location stayed at the center of camera’s field of view. The observational conditions at that time of $\gamma$-trigger were suboptimal. The burst occurred at a zenith distance $\approx 68^\circ$, the sky was bright due to a nearly full moon, and a large part of camera field of view had been covered by the REM dome. The Fig. 1 shows a summary of TORTORA, “Pi of the Sky” and Swift BAT light curves.

**Data Reduction**

The values of the effective air mass at middle time exposure and the seeing as measured by La Silla–Meteo Monitor [2] were $\sim 2.6$ and $\sim 0.9^\circ$, respectively. According to [3] Galactic Extinction value is $E (B-V) = 0.011$ mag which (assuming $R_\nu = 3.1$) implies $A_B = 0.049$, $A_V = 0.034$, $A_R = 0.030$. The TORTORA fast wide-field camera took the data on the field of GRB 080319B from 05:46:22 UT ($t_0 = 26$ minutes before trigger) to 06:15:41.00 ($t_0 = 172$ sec after trigger) collecting $\sim 13320$ unfiltered images with an effective exposure time of 0.13 sec without any temporal gaps between consecutive frames. From 23 sec up to 30 sec after the burst, the REM-telescope was repointing to the location of GRB 080319B after the alert message was received through the GCN notices by the Swift-BAT instrument. The raw images stored in RAID have been processed at the day time by a pipeline including TV-CCD noise subtraction, flat-fielding to compensate vignetting due to objective design, and custom aperture photometry code taking into account non self-averaging pixel statistics caused by the image intensifier tube. Circular aperture photometry was performed with PHOT/DAOPHOT function in IRAF [3].

**LIGHT CURVE STRUCTURE**

TORTORA has tracked a fast rise of optical emission from $t_0 + 10$ sec to $t_0 + 15$ sec, followed by a complex evolution until $t_0 + 45$ sec and a slow decay thereafter. The rise from $V \approx 7.5^m$ to $V \approx 5.5^m$ may be approximated by a $\sim t^4$ power-law originated at $t_0 \approx 0$; while $\gamma$-ray emission started earlier, at $t_0 \approx -4$ sec. The decay since $t_0 + 45$ sec is a $\sim t^{-4.6}$ power-law. Four peaks can clearly be seen in optical data with an inter-peak separation of $\sim 8.5$ sec.

**Observed and Intrinsic Optical Parameters**

The fluxes of the four well-detected optical peaks $F_{opt, 1, 2, 3, 4}$

$$F_{opt} = 827 \times (3.60 \times 10^{-9} \times 10^{-0.4 \times mag})$$

were obtained by using the calibration of [12] and were corrected for galactic extinction (Table 1). Host galaxy reddening correction $A_V$ was applied assuming the mean value reported by [15], $E (B-V) = 0.05$. The isotropic equivalent Luminosity $L_{opt}$ (Table 2) for the

**Table 1. Prompt Optical Parameters of GRB 080319B: Peak Flux.**

| Peak Flux | [$erg cm^{-2} s^{-1}$] |
|-----------|---------------------|
| $F_{opt, 1}$ | $(2.20 \pm 0.16) \times 10^{-8}$ |
| $F_{opt, 2}$ | $(2.18 \pm 0.28) \times 10^{-8}$ |
| $F_{opt, 3}$ | $(1.49 \pm 0.10) \times 10^{-8}$ |
| $F_{opt, 4}$ | $(1.61 \pm 0.10) \times 10^{-8}$ |

For the REM repointing time interval fluxes have been derived using custom elliptic aperture photometry code after summation of 10 consecutive frames with compensated motion of the stars. Unfortunately, it seems impossible to reconstruct the light curve of this interval with any better resolution due to massive blurring of star PSF caused by their motion. For all other intervals, photometry has been performed both with 10-frames (1.3 sec effective exposure) binning, and with original (0.13 sec) time resolution. As a result, we have identified a new peak in the prompt optical light curve. Finally the photometry performed in instrumental system was calibrated towards the $V$ magnitudes of several nearby Tycho2 stars. We have no data on prompt light curve color for GRB 080319B at early times ($t_0 < t < 60$ sec). Thus, no additional color corrections have been applied to TORTORA’s unfiltered data.
well-detected optical peaks is related to the peak flux \( F_{opt, i} \) using the equation

\[
L_{opt} = 4\pi \kappa_{opt}(z) D_T^2(z) F_{opt}
\]  

where \( D_T^2(z) \) is the luminosity distance for the cosmological standard model and \( \kappa_{opt}(z) \) is the cosmological \( \kappa \)-correction that accounts for the transformation of the \( V \) passband in the proper GRB frame:

\[
\kappa_{opt} = \left( \frac{\int V'_{V} \nu V'_{V}^{-\beta} dV}{\int \nu V'_{V}^{-\beta} dV} \right) = \frac{1}{(1+z)^{1-\beta}}
\]

where \( \nu_{V0} \) and \( \nu_{V1} \) are the frequency boundaries of the \( V \) band and \( \beta \) is the power-law index in the optical spectrum \( F_{\nu} \propto \nu^{-\beta} \). For \( \kappa \)-correction we assume \( \beta = 0.50 \pm 0.07 \) as reported by [15]. The optical fluence \( S_{opt, V} \) was determined by numerically integrating the prompt light curve in the interval from the earliest observation to the latest one with a power-law interpolation of the flux in the segments between the experimental points yielding \( S_{opt, V} = (7.17 \pm 1.80) \times 10^{-7} \text{ erg cm}^{-2} \) (1.87 sec < \( t \) < 86 sec). The isotropic equivalent total energy in \( V \) band \( E_{opt, V} \) in the rest frame of the source was determined from the optical fluence \( S_{opt, V} \) using the relation:

\[
E_{opt, V} = \frac{4\pi \kappa_{opt}(z) D_T^2(z) S_{opt, V}}{(1+z)}
\]

yielding \( E_{opt, V} = (1.21 \pm 0.30) \times 10^{51} \text{ erg} \). The complex evolution from \( t_0+15 \text{ sec} \) to \( t_0+45 \text{ sec} \) consists of two well-distinct regions of different peak intensity levels: \( L_{peak, 1, 2} \approx 2.19 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \) from \( t_0+15 \text{ sec} \) to \( t_0+30 \text{ sec} \) and \( L_{peak, 3, 4} \approx 1.55 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \) from \( t_0+30 \text{ sec} \) to \( t_0+45 \text{ sec} \) which roughly correspond to two regions of \( \gamma \)-ray light curve. The event is extreme not only in observed properties but also intrinsically: it is the most luminous event ever recorded at optical wavelengths and has an exceedingly high isotropic-equivalent energy release in \( \gamma \)-rays. The previous record was held in brightness by GRB 990123 [11], GRB 050904 [16], and GRB 061007 [17]. In spite of its initial brightness, the behavior of the afterglow at middle/late time does not appear to be peculiar. The extrapolated luminosity e.g. at 10 hour and at 13 hour after the trigger in the rest frame of the source \( (L_{opt@10h} \approx 3.16 \times 10^{44} \text{ erg s}^{-1} \) and \( L_{opt@13h} \approx 9.77 \times 10^{43} \text{ erg s}^{-1} \) respectively) are comparable with the average luminosity of the afterglow sample detected over the past few years [18].

**FIGURE 1.** The light curve of GRB080319B acquired by TORTORA’s wide-field camera (upper curve) alongside with Swift/BAT \( \gamma \)-ray one (lower curve, light gray color). Also, transient brightness measurements by "Pi of the Sky" optical camera are shown. The Swift/BAT light curve is the sum of all four energy channels. TORTORA data points show both full resolution (original data frames, grey color) and low-resolution (10 images co-added, red color). Full-resolution data are unavailable for the time interval of REM telescope repointing due to massive blurring of object image.

**TABLE 2.** Prompt Optical Parameters of GRB 080319B: Peak Luminosity.

| Peak Luminosity | \( \text{erg s}^{-1} \) |
|-----------------|--------------------------|
| \( L_{peak, 1} \) | \( (7.24 \pm 0.71) \times 10^{49} \) |
| \( L_{peak, 2} \) | \( (7.21 \pm 1.08) \times 10^{49} \) |
| \( L_{peak, 3} \) | \( (4.91 \pm 0.42) \times 10^{49} \) |
| \( L_{peak, 4} \) | \( (5.30 \pm 0.45) \times 10^{49} \) |
Variability Analysis

As reported previously the light curve is approximated by a four nearly equidistant flares with an inter-peak separation of \( \sim 8.5 \) sec in observer frame. The Power Density Spectrum between 10 sec and 50 sec confirms this feature with a 99.999% confidence. When we use the high resolution data from \( t_0 + 40 \) sec to \( t_0 + 50 \) sec a periodicity at a frequency of \( \sim 0.9 \) Hz is detected with a 99% confidence and it may be interpreted as a Lense-Thirring precession or nutation [19].

CONCLUSIONS

The prompt optical emission of the GRB 080319B is peculiar for several reasons: it is the most luminous event ever recorded reaching a visual peak absolute magnitude of \( M_V, peak = -38.4 \) and is the variable object at cosmological distances with the shortest optical periodicity ever discovered. The temporal structures reflect the behaviour of the internal engine (periodicity of \( \sim 8.5 \) seconds for overall emission, four peaks) and the disk precession (\( \sim 1.1 \) second period on the last peak), and imply the newborn stellar-mass black hole accreting from massive disk as an internal engine of this burst.

ACKNOWLEDGMENTS

This work was supported by the University of Bologna Progetti Pluriennali 2003, by grants of CRDF (No. RP1-2394-MO-02), RFBR (No. 04-02-17555 and 06-02-85103), INTAS (04-78-7366), and by the Presidium of the Russian Academy of Sciences Program.

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