FAST OPTICAL VARIABILITY OF A NAILED-EYE BURST—MANIFESTATION OF THE PERIODIC ACTIVITY OF AN INTERNAL ENGINE

G. Beskin1, S. Karpov1, S. Bondar2, G. Greco3, A. Guarnieri4, C. Bartolini4, and A. Piccioni4
1 Special Astrophysical Observatory, Nizhniy Arkhyz, Karachaevo-Cherkesia, Russia
2 Institute for Precise Instrumentation, Nizhniy Arkhyz, Karachaevo-Cherkesia, Russia
3 Astronomical Observatory of Bologna, INAF, Italy
4 Astronomical Department of Bologna University, Bologna, Italy

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ABSTRACT

We imaged the position of the naked-eye burst, GRB080319B, before, during, and after its gamma-ray activity with sub-second temporal resolution using the TORTORA wide-field camera. The burst optical prompt emission, which reached 5.3 mag, has been detected, and its periodic optical variability has been discovered in the form of four equidistant flashes with a duration of several seconds. We also detected a strong correlation (r ≈ 0.82) between optical and gamma-ray light curves with a 2 s delay of the optical emission with respect to the gamma-ray emission. The revealed temporal structure of the optical light curve in comparison with the gamma-ray light curve can be interpreted in the framework of the model of shell collisions in the ejecta containing a significant neutron component. All observed emission features reflect the non-stationary behavior of the burst internal engine—supposedly, a hyperaccreting solar-mass black hole formed in the collapse of a massive stellar core.

Key words: gamma-ray burst: individual (GRB 080319B)

Online-only material: color figures

1. INTRODUCTION

Long-duration gamma-ray bursts (GRBs) are supposedly produced by newborn compact relativistic objects, stellar-mass black holes or highly magnetized neutron stars, during the collapse of the core of massive stars (Piran 2005; Meszaros 2006).

Multicwavelength observations of GRBs are important tools for studying these objects, whose behavior defines the temporal structure of the bursts.

Thereby, the discovery of prompt optical emission in follow-up observations (Akerlof et al. 1999; Vestrand et al. 2005; Yost et al. 2007; Page et al. 2007) has led to the refinement of different GRB models.

However, the insufficient temporal resolution of the observations, typically worse than 10 s, has prevented the clarification of the nature of the bursts.

In order to capture the initial moments of the burst optical emission with high temporal resolution, we have designed and built several wide-field monitoring cameras (Piccioni et al. 1993; Karpov et al. 2005; Molinari et al. 2006). One of these cameras, the TORTORA (Telescopio Ottimizzato per la Ricerca dei Transienti Ottici RApidi), has successfully carried out high temporal resolution observations of the naked-eye burst, GRB080319B (Karpov et al. 2008; Racusin et al. 2008; Beskin et al. 2008). To date, this is the only case study of a GRB’s optical emission from the beginning to the end, with a resolution comparable to that of gamma-ray observations. We discovered the fast periodic variability of the optical emission and its tight correlation, with a two-second lag, to the gamma-ray emission. Both of these reflect the periodic activity of the burst internal engine—likely, a hyperaccreting solar-mass black hole formed in the collapse of a massive stellar core.

The aim of this Letter is to describe the TORTORA observations and data reduction of GRB 080319B (Section 2), then to perform a detailed comparative analysis of the optical and the gamma emission (Section 3), and finally to discuss the nature of the optical emission discovered and its variability (Section 4).

2. OBSERVATIONS

We observed the region of GRB080319B from 30 minutes before the trigger time T, until several tens of minutes after (Karpov et al. 2008; Racusin et al. 2008), with the TORTORA wide-field (24′ × 32′) monitoring camera (temporal resolution 0.13 s; Molinari et al. 2006) mounted on the Rapid Eye Mount (REM) telescope at La Silla, Chile (Zerbi et al. 2001).

After receiving the coordinates of GRB 080319B communicated by the Swift satellite, the position of the burst was moved from the edge of the TORTORA field of view toward its center. Therefore, from T + 24.5 s to T + 31 s the REM telescope performed an automatic repointing (see Figure 1).

The acquired data were processed by the standard TORTORA pipeline including CCD dark current subtraction and flat fielding. The reduction was performed by a customary code accomplishing circular aperture photometry and was then verified by IRAF DAOPHOT code, except for the data acquired during the REM repointing. Over that period of time, the target and nearby star images are stretched up to five times on the time scale of a single exposure due to the motion of the field of view.

Such motion significantly lowers the signal-to-noise ratio and makes it impossible to perform reliable flux measurements on every single frame. To overcome this challenge, we performed the summation of sets of 10 non-overlapping frames, spatially shifting them to compensate for the motion of the telescope and to obtain profiles of the trails with a signal-to-noise ratio nearly equal to 1 in other intervals of the light curve (see Figure 2(c)). Then we processed the co-added frames through a customary elliptic aperture photometry code as well as by means of point-spread function fitting, which provided consistent results. The effective temporal resolution for this interval is 1.3 s. For all other time intervals, the photometry has been performed with both full (0.13 s exposure) and low temporal resolution
(1.3 effective exposure for 10 co-added images). Then, we obtained the instrumental magnitudes of the object, both for the REM repointing interval and the other parts of the light curve. These were calibrated to the Johnson V-band using several nearby Tycho-2 stars. The light curve of one of the comparison stars, processed and calibrated in the same way as the transient, is shown in Figure 2(b). No significant deviation from the constant flux, neither in high resolution nor in low resolution mode, is present, which suggests that the variations seen in the light curve of the transient are real.

A quick-look, low-resolution light curve (excluding the data during the REM repointing interval) has been published (Karpov et al. 2008; Racusin et al. 2008). Our complete full resolution light curve, along with the low-resolution one (after the restoring of the gap), is shown in Figure 2.

3. ANALYSIS OF OPTICAL LIGHT CURVE

3.1. Periodicity of Optical Emission

The light curve of GRB080319B clearly shows four peaks with similar amplitudes, durations, and shapes (see Figure 2(c)). We approximated the low-resolution data by the sum of four components described by a simple function smoothly connecting two power laws (Kocevski et al. 2003)

$$F = F_0 \left( \frac{t}{T_0} \right)^r \left[ \frac{d}{d + r} + r \left( \frac{r + 1}{d + r} \right)^{r+1} \right]^{-\frac{r+d}{d+1}}$$

(1)

(where $t$ is the time since trigger) whose parameters are listed in Table 1. The fit over the interval from $T = 0$ s to $T = 100$ s has a $\chi^2 = 33.4$ for 61 degrees of freedom. The distances between peaks are the same within the errors: $\Delta T \approx 8.5$ s in the observer frame, which corresponds to 4.4 s in the rest frame at $z = 0.937$ (Racusin et al. 2008; Beskin et al. 2008).

We then performed a Fourier analysis of the central part of the light-curve (full-resolution one, with data points finely sampled with 0.13 s separation), defined as the interval between the first and the last peak extended by the mean distance between peaks, that is from $(T_1 - 0.5\Delta T) = 14.05$ s to $(T_d + 0.5\Delta T) = 48.65$ s.

The power density spectrum of this light-curve interval after removal of the linear trend is shown in Figure 3(a). A feature at $f_0 \approx 0.12$ Hz (marked by a vertical line) is clearly visible and corresponds to the mean distance between the light-curve peaks, alongside the low-frequency components of the overall two-level step-like structure of this part of the light curve (not completely compensated for by linear trend removal).

Its significance, however, strongly depends on the assumed model of the shape of the underlying continuum component—the zero hypothesis. Reconstructing it from surrounding points, as an arithmetic mean of two nearest bins, gives a 24.5 times excess of the actual spectral density over the continuum (dotted horizontal line in Figure 3(a)). Assuming the standard exponential probability distribution of power density estimates over the mean value, it corresponds to $p = 3 \times 10^{-5}$

![Figure 1](image1.png)  
(Deployment of prompt optical emission from GRB080319b as shown by the TORTORA camera. Sums of 10 consecutive frames with 1.3 s effective exposures are shown for the gamma-ray trigger time ($T = 0$ s), the maximum brightness time during the first peak ($T = 20.5$ s), two middle-part moments ($T = 26.4$ s and $T = 28.4$ s), the last peak ($T = 36.5$ s), and during early afterglow ($T = 80$ s) stages. Image size is 2.5 x 2.5. Circles mark the transient (in the center) and the brightest of the nearest field stars used for photometric calibration, whose light curve is shown in Figure 2(b). (A color version of this figure is available in the online journal.)

![Figure 2](image2.png)  
(A) Comparison Star

![Figure 2](image3.png)  
(Object

![Figure 2](image4.png)  
(Notes. Here, $T_0$ and $F_0$ are the peak maximum positions relative to trigger time and flux, while $r$ and $d$ are the power-law indices of their rising and declining parts. $\Delta T$ is the distance between the peak and the next one.)

| Table 1 | Best-fit Parameters for the Decomposition of the Light Curve into Four Peaks with Shape Described by the Kocevski et al. (2003) Profile (see Equation (1)). Shown in Figure 2(c) |
|---------|--------------------------------------------------------------------------------------------------|
| $T_0$, s | $F_0$, Jy | $r$ | $d$ | $\Delta T$, s |
| 18.3 ± 0.3 | 23.2 ± 0.6 | 4.0 ± 0.4 | −5.4 ± 4.1 | 8.7 ± 0.4 |
| 27.0 ± 0.3 | 13.4 ± 3.4 | 24.8 ± 8.3 | −9.7 ± 4.9 | 9.1 ± 0.4 |
| 36.1 ± 0.2 | 11.4 ± 1.7 | 25.9 ± 7.6 | −22.0 ± 17 | 8.3 ± 0.5 |
| 44.4 ± 0.5 | 15.1 ± 1.8 | 21.9 ± 3.3 | −5.1 ± 0.2 |
Figure 2. Light curve of GRB080319B acquired by the TORTORA wide-field camera (c), approximated by the sum of four peaks with parameters listed in Table 1. Residuals of such an approximation are shown in (d). The gamma-emission, presented for comparison in (a), started at $T \approx -4$ s and faded at $T \approx 57$ s. The light curve of comparison star (b) shows no significant features.

(A color version of this figure is available in the online journal.)

Figure 3. (a) Power density spectrum of the plateau phase (from $T + 14$ s to $T + 49$ s) of the naked-eye burst optical light curve with the linear trend removed. (b) Power density spectrum of the same interval of a bright nearby star light curve.

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probability of the zero hypothesis after correcting for the amount of 133 bins in the whole spectrum.

A more conservative estimate can be made modeling the undetrended light curve with the sum of red and white noise components, approximating its spectral density excluding the bin containing the periodic component in question. We generated a large set of such processes and detrended each of them in the same way as the original data. The mean values of spectral density of such artificial data are shown as a smooth solid curve in Figure 3(a). The periodic feature then shows the 13.4 times excess over the mean zero-hypothesis level, which corresponds to a $p = 2 \times 10^{-4}$ significance level taking into account the full number of bins in the complete spectra (133 bins).

The power spectrum of the comparison star, derived in the same way and for the same light-curve region, does not display any features with significance better than 0.01 in a single bin (0.35 for total number of 133 bins) with respect to the mean noise level (see Figure 3(b)), neither at the frequency of the peak seen in the transient spectrum nor anywhere else. This rules out the possible artificial nature of the discovered periodicity.

Thus, for the first time, we have a clear detection of periodic variations of a GRB prompt optical emission on a few seconds time scale.

To study short time-scale optical variability, the smooth curve—formed by four fitted peaks—has been subtracted from the original full-resolution high-resolution data. The residuals are shown in Figure 2(d). The power spectral analysis of different sub-intervals of the burst revealed no signature of a variability in the 0.1–3.5 Hz (0.3–10 s) range with power exceeding 15% before and 10% after the REM repointing.

3.2. Correlation between Optical and Gamma-ray Emission

In order to reveal the similarity between optical and gamma-ray light curves and to filter out the stochastic variability of the latter, we performed a cross-correlation analysis. Again, we solely used the plateau phase of the light curves, excluding the first and last 12 s of the burst, both in optical and in gamma, as they are obviously highly correlated (Beskin et al. 2008).

For the low-resolution data, with a 1.3 s bin size, the correlation coefficient is as high as 0.82 with a significance level of $5 \times 10^{-7}$ when the optical light curve is shifted 2 s back with respect to the gamma-ray one (see Figure 4). The correlation of unshifted data, at the same time, is as small as 0.42 with a significance of 0.03. Correspondingly rebinned gamma-ray data show the same four quasi-equidistant peaks as the optical ones (lower panel of Figure 4). Correlation of high-resolution data (0.13 s bin) is systematically lower due to higher amount of noise in it. Quasi-periodic variations of cross-correlation for low-resolution data are due to a sharp feature in gamma-ray data at around $T + 30$ s falling into either one or two bins of the rebinned light curve.

Nevertheless, the periodic variability components seen in the optical light curve are not manifested in the power density spectrum of the corresponding intervals of the gamma-ray one. This is most likely due to a significant amount of stochastic, shot noise-like variability of gamma emission which spans from tens to fractions of seconds (Margutti et al. 2008; C. Guidorzi 2010,
private communication), possibly masking any low-amplitude regular structure in the data. Indeed, the non-stationary ejection of matter from the burst internal engine most likely modulates not the amplitudes of flares in the light curve, but their rate (or mean distance between them) which tracks the smooth optical light-curve intensity, and found that for nearly 90% of realizations the power spectra of simulated light curves do not show any features on the frequency in question, while keeping the correlation with optical light curve roughly as high as \( r = 0.82 \) observed. Obviously, there are other possible types of stochastic process modulation which may be revealed only in smoothed data, but not in the power spectrum.

4. DISCUSSION

The \( \Delta t \approx 2 \) s delay of the optical flash relative to the gamma-ray one inevitably suggests that they were generated in different parts of the ejecta. More precisely, the optical photons came from a distance \( \Delta R \approx 2c\Gamma^2\Delta t(1+z)^{-1} = 1.5 \times 10^{16}\Gamma_{500}^{-2} \) cm away from the central engine, where \( \Gamma_{500} \) is the Lorentz factor in units of 500 (Piran 2005; Li & Waxman 2008).

This result and other peculiarities we detected in the naked-eye burst clearly contradict the proposed emission generation mechanisms based on various kinds of interactions between a single ensemble of electrons and photons that they generate: synchrotron or inverse Compton ones (Racusin et al. 2008; Kumar & Panaiteescu 2008; Fan & Piran 2008), the model of two internal shocks, forward and reverse (Yu et al. 2009), and a relativistic turbulence model (Kumar & Narayan 2009). On the other hand, the fast rise and the similarity of durations of all four optical flashes rule out an external shock (both forward and reverse) as a source of optical emission (Zou et al. 2009).

Two internal shock models have also been proposed, in which optical and gamma-ray flashes are generated by a synchrotron mechanism in different parts of the ejecta—the larger the photon energy is the closer it is to the central engine. These models are the residual collisions model (Li & Waxman 2008) and the model with significant input of a neutron component (Fan et al. 2009). In these scenarios, the gamma emission is produced at a distance of \( 10^{14}–10^{15} \) cm from the central due to the electron heating caused by shock waves of colliding proton shells. In the former model, optical quanta are generated in an optically thin plasma during the collisions of “residual” shells (each shell being the result of the merging between a large number of thinner “original” shells), far (\( \gtrsim 10^{16} \) cm) from the central engine (Li & Waxman 2008). In the latter model, the optical emission is generated by the electrons produced in \( \beta \)-decay of neutrons, which may reach a distance of \( R \sim 10^{16} \) cm without interactions with other components of the ejecta. The decay products, protons and electrons, collide with faster proton shells ejected later, producing secondary internal shocks which heat the electrons, generating synchrotron optical emission. Both models easily explain the 2 s delay observed in the optical light curve, as well as its general smoothness on the 0.1–1 s time scale, in contrast to high level of stochastic variability in the gamma-ray emission (Margutti et al. 2008). On the other hand, the great difference between naked-eye burst optical and gamma-ray fluxes (\( F_\text{opt}/F_\gamma \approx 10^7 \); Racusin et al. 2008) is more naturally explained in a neutron-rich model (Fan et al. 2009).

As a matter of fact, a large amount of neutrons is unavoidable in bright GRBs like GRB080319B (Derishev et al. 1999; Pruet et al. 2003). This model, therefore, is preferable, and our results may provide strong evidence of the existence of a significant neutron component in the ejecta.

In brief, we conclude that optical and the gamma emission of the naked-eye burst were generated at different distances from the central engine. Such a conclusion is a direct consequence of the detected similarity of shifted optical and gamma-ray light curves. Such a similarity depends neither on particular mechanisms of conversion of mechanical to internal electron energy, nor on the emission mechanisms. Moreover, this effect cannot be caused by the density or velocity variations inside the ejecta, such as those already observed on a time scale of several tens of minutes in afterglows of other GRBs (Jakobsson et al. 2004; Bersier et al. 2003). Obviously, it would be impossible for the relativistic ejecta itself to display similar structures and dynamics, especially periodic behaviors, in regions separated by \( 10^{16} \) cm. Therefore, we have to conclude that these variations have the same cause—namely, the cyclic variations of internal engine activity (each flash of the light curve corresponds to one of its four episodes).

The detected non-stationarity of the ejection flow can be a result of non-stationary accretion due to periodically triggered gravitational instability (Masada et al. 2007) in the hot inner part of one solar mass hyperaccreting disk, around a black hole with a mass of about three solar masses, formed in the collapse of a massive star (Woosley 1993; Zhang et al. 2004).

Such a disk must contain a large amount of neutrons (Pruet et al. 2003), and the four peaks detected in the optical light curve reflect the four episodes of accretion activity leading to the ejection of matter. The matter forming the inner part of the disk (fragmented due to instabilities) becomes the elements of the jet. The collisions of these fragments generate the internal shocks in the ejecta.

5. CONCLUSIONS

The strategy of a wide-field monitoring with high-temporal resolution (Karpov et al. 2010; Beskin et al. 2010), implemented in the TORTORA camera, made it possible to perform, for
the first time, a detailed investigation of the optical flash accompanying GRB080319B.

We discovered the periodic variability of its optical emission with a characteristic time scale of 8.5 s (4.2 s in source frame), manifested in the four similar light-curve peaks. The amplitude of stochastic variations does not exceed 10%–15% on the 0.1–1 s time scale, in contrast to highly variable gamma-ray emission. The comparison of light curves reveals a 2 s delay between the optical and the gamma-ray emission, which is clear despite a similarity between the overall temporal structures. Correspondingly shifted light curves have a correlation coefficient of \( r = 0.82 \) over the \( T + 10 \text{ s} - T + 47 \text{ s} \) interval.

The acquired data and their analysis led us to the following conclusions:

1. the emission of GRB080319B in the optical and gamma-ray ranges is generated in different regions of the ejecta, which clearly contradicts a number of models suggested as an explanation of this burst (Racusin et al. 2008; Kumar & Panaitescu 2008; Fan & Piran 2008; Yu et al. 2009; Kumar & Narayan 2009);

2. peculiarities of the optical emission variations in comparison to the gamma-ray ones can naturally be explained in the framework of models with either residual collisions of shells (Li & Waxman 2008) or significant neutron component in the outflow (Fan et al. 2009). As the latter model provides a better explanation of various aspects of the observational features of the burst, we suggest the presence of a vast amount of neutrons in the jet;

3. the four peaks characterizing the optical light curve reflect the periodic modulation of the accretion from the massive disk around the newborn black hole, formed in the core-collapse of a massive star.

Our important data on the detailed structure of GRB080319B optical emission, never acquired before, suggest that the development of methods and instruments for wide-field monitoring with high temporal resolution should continue. Especially important is the construction of instruments able not only to detect an optical transient, but also to simultaneously acquire the spectral and polarimetric information from optical photons in real time (Beskin et al. 2010).

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