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Variability of the Naked-Eye Burst prompt optical emission as a manifestation of its central engine periodic activity.

G. Beskin, S. Karpov
Special Astrophysical Observatory of Russian Academy of Sciences, Russia
E-mail: `beskin@sao.ru`

S. Bondar
Institute for Precise Instrumentation, Russia

A. Guarnieri, C. Bartolini
Astronomical Department of Bologna University, Italy

G. Greco
Astronomical Observatory of Bologna, INAF, Italy

A. Biryukov
Sternberg Astronomical Institute of Moscow State University, Russia

Naked-Eye Burst is the only event observed in optical and gamma-ray ranges simultaneously with sufficiently high temporal resolution. This opens unprecedented possibilities for testing various models of both emission generation and the central engine behaviour during the burst. The temporal properties observed, along with tight optical to gamma relation, suggest the intrinsic periodicity of internal engine, which is supposedly a newborn stellar-mass black hole surrounded by an unstable precessing massive accretion disk.

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PoS(Texas 2010)259

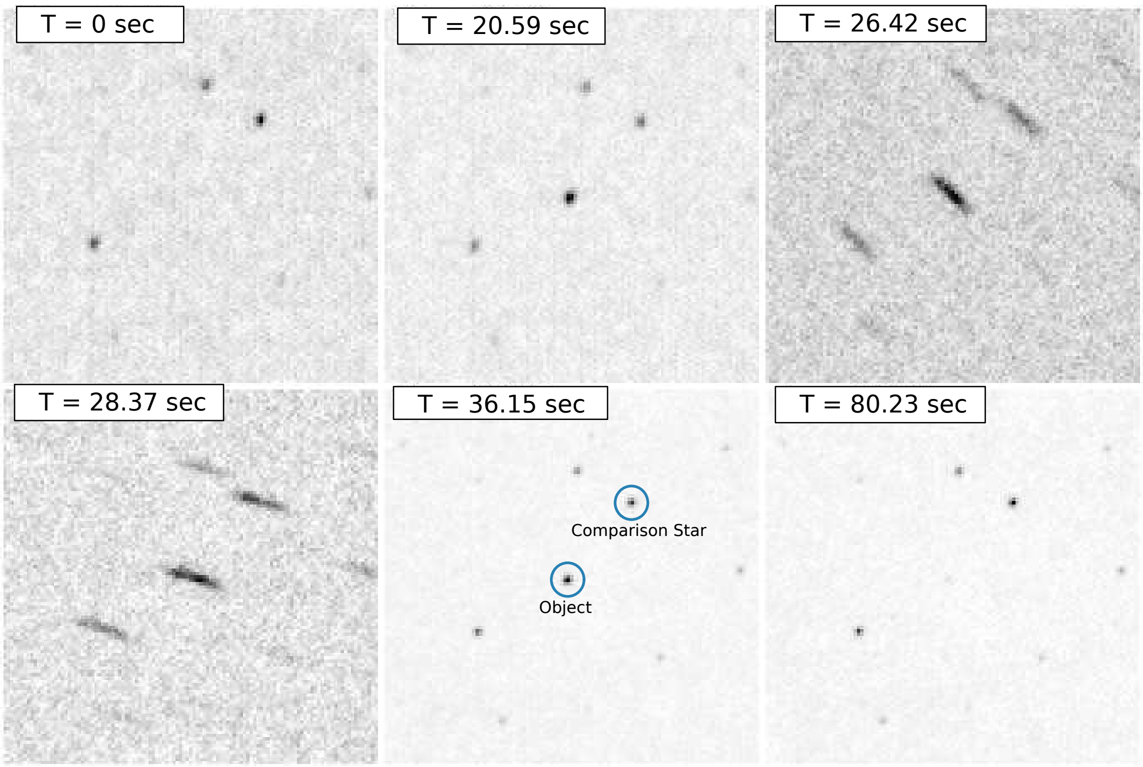

Figure 1: The development of prompt optical emission from GRB080319b as seen by TORTORA camera. Sums of 10 consecutive frames with 1.3 s effective exposures are shown for the gamma-ray trigger time ($T = 0$ s), the maximum brightness time during the first peak ($T = 20.5$ s), two middle-part moments ($T = 26.4$ s and $T = 28.4$ s), at the last peak ($T = 36$ s) and during early afterglow ($T = 80$ s) stages. Image size is 2.5 x 2.5 degrees. The third and fourth images display deformed star profiles as during this time (since $T+24$ s till $T+31$ s) REM robotic telescope (which has TORTORA camera mounted on top) repointed after receiving the burst information from Swift. Initially, burst position was on the edge of field of view, as a result of repointing it moved to the center of field of view, which resulted in better data quality.

March 19 and 20, 2008 became the most fruitful days for wide-field monitoring systems around the world. It brought up 5 GRBs in a row, all within 24 hours, one of which, GRB080319B[16], is the brightest ever seen in gamma-rays and optical range, and the first one to be detected by monitoring systems. Its field of view had been images before, during and after the gamma event by "Pi of the Sky", RAPTOR Q and TORTORA[8] cameras.

We observed the region of GRB080319B[16] from 30 minutes before the trigger time T, until several tens of minutes after [8], with TORTORA wide field (24x32 degrees) monitoring camera (temporal resolution 0.13 s) [14] mounted on the REM telescope at La Silla (Chile). 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 towards its centre. Therefore from $T+24.5$ s till $T+31$ s the REM telescope performed an automatic repointing.

The acquired data were processed by the standard TORTORA pipeline including CCD read-out, dark noise subtraction and flat-fielding. The reduction were performed by a customary code

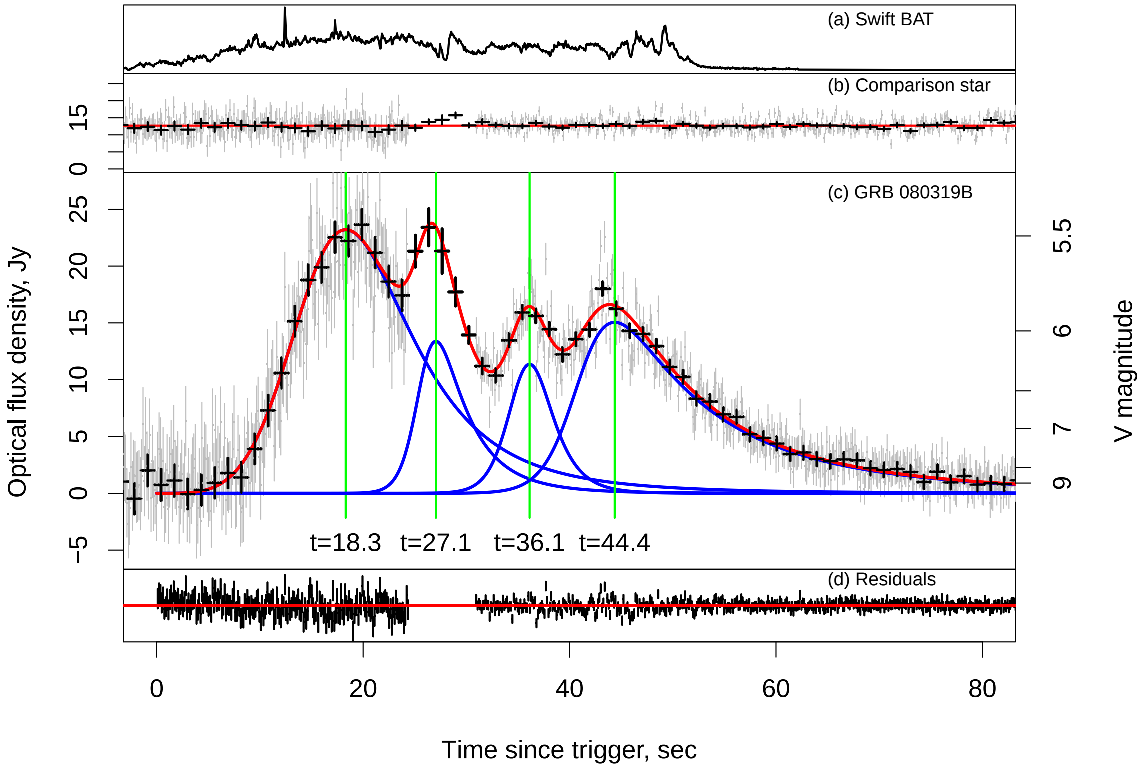

Figure 2: The light curve of GRB080319B acquired by TORTORA wide-field camera (lower middle panel). The gamma-emission, presented for comparison in upper panel, started at $T \approx -4$ s and faded at $T \approx 57$ s.

accomplishing circular aperture photometry and then verified by IRAF DAOPHOT code, except the data acquired during the REM repointing. Over that period of time, the target and nearby stars images are stretched up to 5 times on the time scale of a single exposure due to the motion of the field of view. To compensate the corresponding decrease of the signal-to-noise ratio, we performed the summation of sets of 10 non-overlapping frames, spatially shifting them to compensate the motion of the telescope and to obtain profiles of the trails with a signal-to-noise ratio nearly equal to one in other intervals of the light curve (see Figure 2).

We clearly detected the transient optical emission since approximately 10 seconds after the trigger. It then displayed fast $\sim t^4$ rise, peaked at $V \approx 5.5^{\mathrm{m}}$, demonstrated 1.5-2 times variations on a several seconds time scale and decayed as $\sim t^{-4.6}$ until went below TORTORA detection limit at about hundred seconds since trigger. The gamma emission itself ended at 57th second.

The light curve clearly shows four peaks with similar amplitudes, durations and shapes. We stress that distances between peaks are nearly the same within the errors, and are around 8.5 s in observer frame, which corresponds to 4.4 s in the rest frame at z=0.937. Power density spectrum of the light curve plateau phase also shows the feature on the corresponding frequency with significance of $p = 3 \cdot 10^{-9}$ (see left panel of Figure 4).

Power spectral analysis of different sub-intervals of the burst revealed the signature of a periodic intensity variations during the last peak, since $T + 40$ s till $T + 50$ s, with the significance of

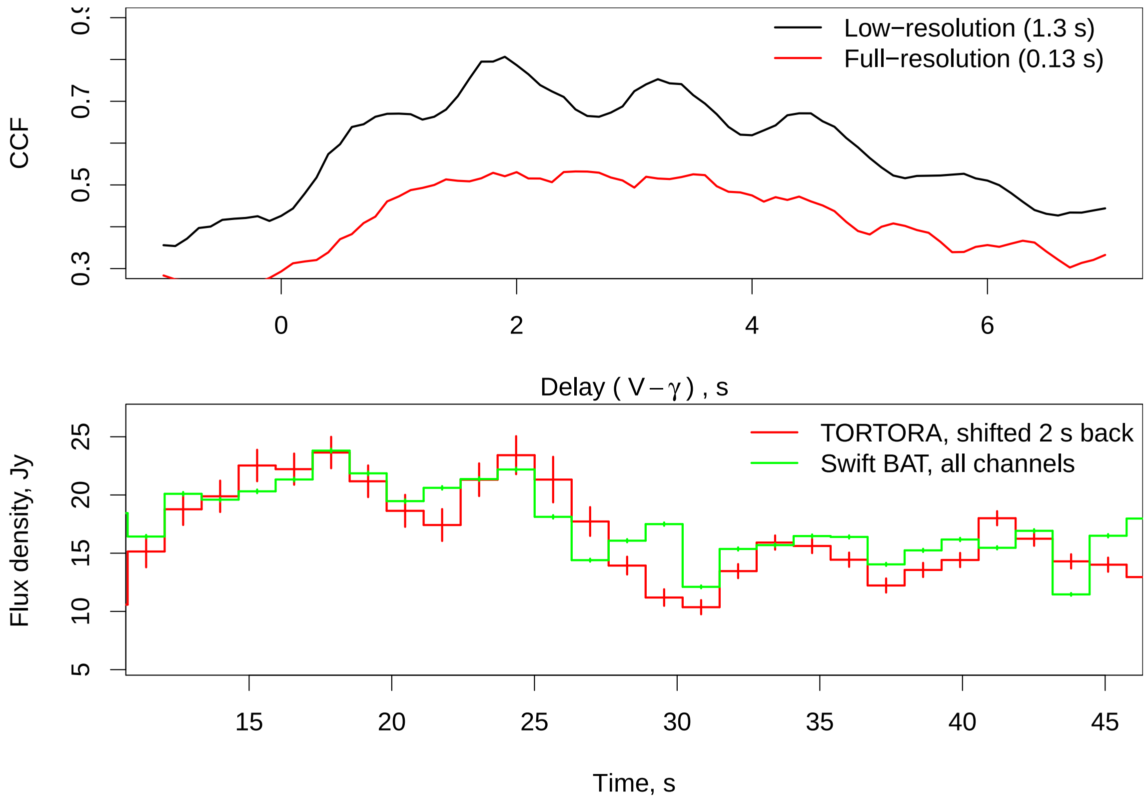

Figure 3: Cross-correlation of the Swift-BAT gamma-ray (data from all energy channels with 64 ms temporal resolution) and TORTORA (data with 0.13 s and 1.3 s resolution) optical fluxes for the main (plateau) phase of the burst emission. Also, the TORTORA optical flux shifted back 2 seconds along with correspondingly rebinned Swift-BAT gamma-ray flux. Gamma-ray curve is arbitrarily scaled and shifted for illustrative purposes.

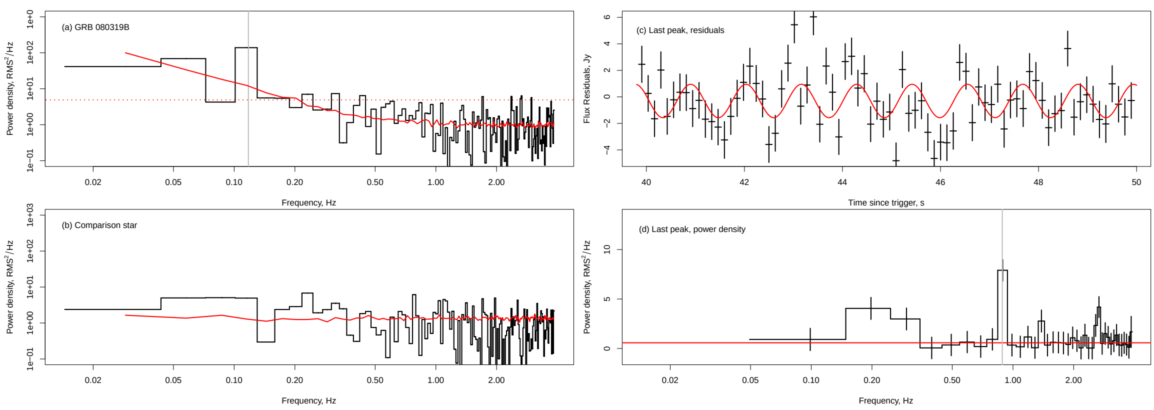

Figure 4: (a) Power density spectrum of plateau phase (since $T+14$ s till $T+49$ s) of the Naked-Eye Burst optical light curve with linear trend removed. (b) Power density spectrum of the same interval of bright nearby star light curve. (c) Optical flux for a $T+40$ s – $T+50$ s interval (last peak) with the approximation shown in right panel of Figure 2subtracted. (d) Power density spectrum of these data.

$p = 2.4 \cdot 10^{-5}$, amplitude of 9% and the period of 1.13 s (see right panel of Figure 4). No other intervals of the light curve show any variability in 0.1-3.5 Hz (0.3-10 s) range with power exceeding 15% before and 10% after the REM repointing. Neither comparison stars nor background display any similar periodic feature during either the whole time interval or the last peak.

To compare the temporal structure of optical and gamma-ray light curves we performed the cross-correlation analysis, using the plateau phase only, excluding the first and last 12 seconds of the burst both in optical and in gamma, which are obviously highly correlated[2]. The correlation of low-resolution data is as high as 0.82 ($p = 5 \cdot 10^{-7}$) when optical light curve is shifted 2 seconds back. Correspondingly rebinned gamma-ray data demonstrate the same four nearly equidistant peaks as optical ones (see Figure 3).

This is the first detection of a close relation between the temporal structures of the optical and gamma-ray prompt emission. In our case, the gamma-ray burst itself precedes the optical flash by two seconds. This feature, along with the periodicities we detected, have a serious physical implications for the models of the event, as they clearly contradict [3] the proposed emission generation mechanisms based on various kinds of interactions between a single ensemble of electrons and photons they generate – synchrotron or inverse Compton ones [17, 10, 5], the model of two internal shocks, forward and reverse [19], and a relativistic turbulence model [9]. 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 [21].

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, the closer it to the central engine. These models are the residual collisions model [11] and the model with significant input of neutron component [6]. In these scenarios, the gamma emission is produced at a distance of 10^{14}-10^{15} cm from the center 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 ($\sim 10^{16}$ cm) from the central engine [11]. In the latter model, the optical emission is generated by the electrons produced in β-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 two-second delay observed in the optical light curve, as well as its general smoothness on 0.1-1 s time scale, in contrast to high level of stochastic variability in the gamma-ray emission [12]. On the other hand, the great difference of Naked-Eye Burst optical and gamma-ray fluxes ($F_o/F_\gamma \sim 10^3$) [17] is more naturally explained in a neutron-rich model [6]. As a matter of fact, a large amount of neutrons is unavoidable in bright gamma-ray bursts like GRB080319B [4, 15]. This model, therefore, is preferable, and our results may be a strong evidence of the existence of a significant neutron component in the ejecta.

In brief, we conclude that optical and gamma emission of Naked-Eye Burst were generated at different distances from the central engine. Such conclusion is a direct consequence of the detected similarity of shifted optical and gamma-ray light curves. Such similarity depends neither on particular mechanisms of conversion of mechanical to internal electron energy, nor on the emission mechanisms. Moreover, this effect can not be caused by the density or velocity variations inside

PoS(Texas 2010)259

the ejecta, such as those already observed on a time scale of several tens of minutes in afterglows of other gamma-ray bursts [7, 1]. Obviously, it would be impossible for the relativistic ejecta itself to display similar structures and dynamics, especially periodic behaviours, 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 [13] 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 [18, 20].

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PoS(Texas 2010)259