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Letter to the Editor

Detection of an optical transient following the 13 March 2000 short/hard gamma-ray burst⋆

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Abstract. We imaged the error box of a gamma-ray burst of the short (0.5 s), hard type (GRB 000313), with the BOOTES-1 experiment in southern Spain, starting 4 min after the γ–ray event, in the I-band. A bright optical transient (OT 000313) with $I = 9.4 \pm 0.1$ was found in the BOOTES-1 image, close to the error box (3σ) provided by BATSE. Late time $VRIK'$-band deep observations failed to reveal an underlying host galaxy. If the OT 000313 is related to the short, hard GRB 000313, this would be the first optical counterpart ever found for this kind of events (all counterparts to date have been found for bursts of the long, soft type). The fact that only prompt optical emission has been detected (but no afterglow emission at all, as supported by theoretical models) might explain why no optical counterparts have ever been found for short, hard GRBs. This fact suggests that most short bursts might occur in a low-density medium and favours the models that relate them to binary mergers in very low-density environments.

Key words. gamma rays: bursts – optical transients – techniques: photometric – cosmology: observations

1. Introduction

Gamma Ray Bursts (GRBs hereafter) are flashes of cosmic high energy photons, and they remained for 25 years one of the most elusive mysteries for high energy astrophysicists, the main problem being the lack of knowledge about the distance scale. The detection of counterparts at other wavelengths for the long duration, soft GRBs, revealing their cosmological origin (see van Paradijs et al. 2000 for a recent review). Thus, counterparts to about 30 bursts have been discovered so far with about 25 redshifts measured, but all of them belong to the so called long duration (∼20 s), soft bursts class that comprises about 75% of all GRBs (Mazets et al. 1981). There are evidences that the two classes of bursts are different: whereas long bursts have softer spectra, short bursts have harder spectra (Dezalay et al. 1996). The latter ones comprise about 25% of all GRBs (Kouvelioutou et al. 1993) and their origin still remain a puzzle. No counterparts at longer wavelengths have been found yet in spite of intense efforts in order to detect the

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⋆ Based in part on observations made with the BOOTES instruments in South Spain.

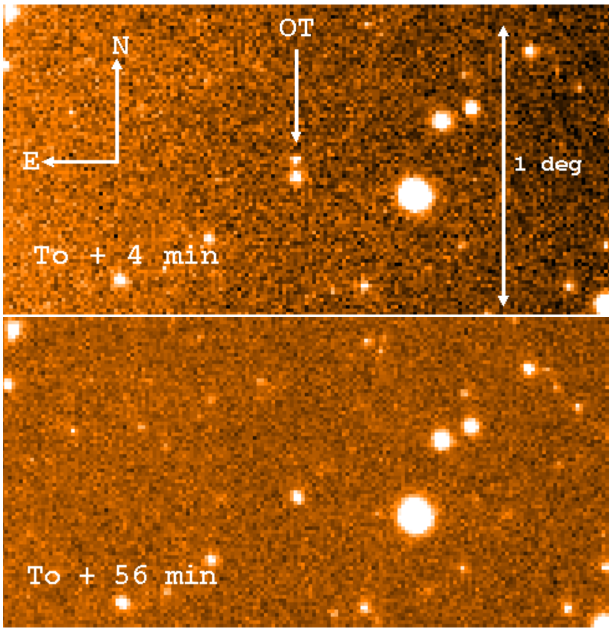

Fig. 1. 2.1° × 1.1° fields in the I-band containing a fraction of the BATSE GRB error box. 13 Mar., UT 21 h 17 min (*upper panel*) and 13 Mar., UT 22 h 13 min (*left panel*). The position of the OT 000313 is marked with an arrow at the center of the image. North is upward and East is to the left. The limiting magnitude is I = 12.0 for the second image.

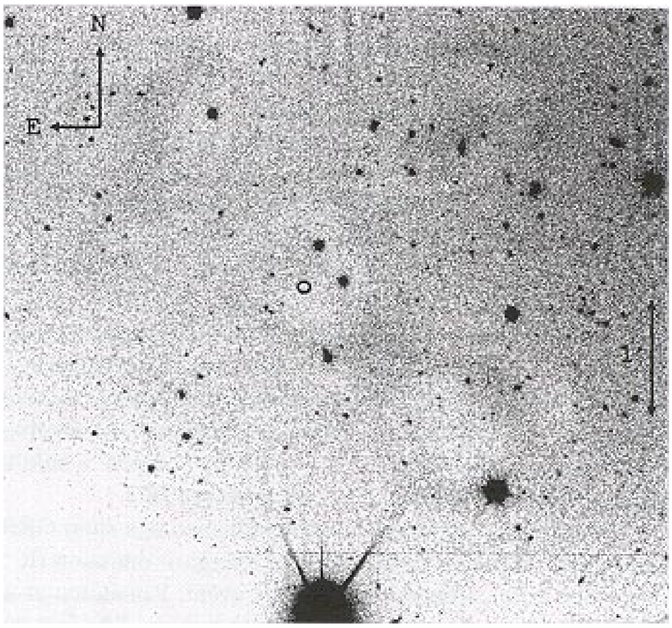

Fig. 2. The deep I-band image obtained at the position of the OT 000313 with the NOT on 31 Mar. 2001. The total integration time was 1800–s. The circle shows the 3″ radius error box for the OT derived from the BOOTES-1 image. The bright star at the bottom is the star 4′ south of the OT in Fig. 1. The field is 2.9′ × 2.1′ with North upward and East to the left.

optical, infrared and radio counterparts to several short, hard bursts (Kehoe et al. 2001; Gorosabel et al. 2002; Hurley et al. 2002; Williams et al. 2002). Therefore, one of the remaining GRB mysteries is whether the origin of the two populations are substantially different from one another.

Here we present the results of a follow-up observation for one of these short/hard events. GRB 000313 was detected on 13 March 2000, UT 21 h 13 min 04 s by the Burst and Transient Source Experiment (BATSE) instrument aboard the Compton Gamma-ray Observatory (trigger number 8035). The single–peaked gamma–ray burst lasted 0.768 ± 0.458 s, showed substructure and was possibly detected below 50 keV. It reached a peak flux (50–300 keV) of ~1.2 (±0.1) × 10^{-7} erg cm^{-2} s^{-1} and a fluence (≥25 keV) of ~2.6 (±1.7) × 10^{-7} erg cm^{-2}. The gamma-rays properties as well as the duration of the burst make from GRB 000313 a clear short/hard gamma-ray burst. The original BATSE position reported through the GCN/BACODINE Network (Barthelmy et al. 1998) was RA(2000) = 13h 31m, Dec(2000) = +27°10′ which was later on refined to RA(2000) = 13h 11m, Dec(2000) = +10°14′.

2. Observations

We obtained I-band and unfiltered images with the wide field CCD cameras of the Burst Observer and Optical Transient Exploring System (BOOTES-1) (Castro-Tirado et al. 1999a) beginning 4 min after the event (13 Mar., UT 21 h 17 min). The image taken with the ultrawide field CCD camera (a 1524 × 1024 pixel CCD attached to a 18-mm f/2.8 lens yielding 1.′64/pixel) covered the original BATSE error box whereas a mosaic of 9 images was performed with the wide field CCD camera (a 1524 × 1024 pixel CCD attached to a 50-mm f/2.0 lens yielding 0.′64/pixel) in order to cover the full error box. The narrow field CCD camera at the Cassegrain focus of the 0.3-m BOOTES-1 telescope (yielding 2″/pixel) imaged part of the field starting on 14 March, 00 h 05 min (4.8 hr later), once the OA was confirmed by the BOOTES team. Further observations were made the same night with the CCD camera at the 1.0-m Jacobus Kapteyn Telescope (JKT) at La Palma under very poor seeing conditions and with the 1.55-m Telescope at the U.S. Naval Observatory (USNO) in Flagstaff. Late time observations were obtained with the MAGIC NIR camera on the 1.23-m telescope at Calar Alto (CAHA) and with the ALFOSC instrument on the Nordic Optical Telescope (NOT) at La Palma. Table 1 report the list of observations. All frames were de-biased and flat-fielded using standard procedures.

3. Results

A comparison of the frames acquired by the BOOTES-1 wide field CCD on Mar. 13, 21 h 17 min UT and Mar. 13, 22 h 09 min UT revealed an optical transient (OT) (see Fig. 1) at RA(2000) = 13h 50m 07.9s, Dec(2000) = +31° 16′ 49″ (±3″) (Castro-Tirado et al. 2000). The object is not detected in the rest of BOOTES-1 images covering the OT position that were taken during the night, starting at 22 h 09 min UT. Using aperture photometry software, we could determine the magnitude of the optical transient in the image as I = 9.4 ± 0.1, by comparison with secondary standards in the field (Henden 2000). The object is not present in the simultaneous ultrawide field CCD frame taken with the 18 mm lens at 21 h 17 min UT, but only an upper limit of R > 9.1 can be derived, which explains

Table 1. Log of the OT 000313 optical and near-infrared follow-up observations.

Date	Time (UT)	Telescope	Filter	Exposure time (s)	Magnitude
13 Mar. 00	21:17	0.05 BOO	I	300	9.4 ± 0.1
13 Mar. 00	22:13	0.05 BOO	I	300	>12.0
14 Mar. 00	02:02	0.3 BOO	–	9 × 120	>19.0
14 Mar. 00	04:00	1.0 JKT	B	600	>20.1
14 Mar. 00	04:12	1.0 JKT	V	600	>19.3
14 Mar. 00	04:25	1.0 JKT	R	2 × 300	>19.0
14 Mar. 00	04:35	1.0 JKT	I	2 × 300	>18.0
14 Mar. 00	05:11	1.5 USNO	I	60	>20.2
14 Mar. 00	06:16	1.5 USNO	R	300	>21.4
14 Mar. 00	07:19	1.5 USNO	I	900	>21.6
23 Apr. 00	22:00	1.2 CAHA	K'	2400	>18.0
28 Apr. 00	00:00	2.5 NOT	I	3 × 600	>22.4
22 Mar. 01	02:20	2.5 NOT	V	3 × 750	>23.4
30 Mar. 01	00:00	2.5 NOT	R	4 × 900	>24.0
31 Mar. 01	22:00	2.5 NOT	I	6 × 300	>23.5
20 May 02	02:00	2.5 NOT	R	15 × 600	>24.5

the non-detection. Late-time observations, carried out between 40 days and ~2 year later, have failed to reveal any quiescent source within the OT error circle down to $V \sim 23.5$, $R \sim 24.5$, $I \sim 23.5$ and $K' \sim 18.0$ (Fig. 2).

4. Discussion

4.1. The reality of the object

The OT is point-like, with the same point-spread-function (PSF) as other field stars. The PSF of the OT image (and also of comparison stars in the field) was fitted with a two dimensional Gaussian function, making use of the nonlinear least-squares Marquardt-Levenberg algorithm. From the fitted profiles it follows that the OT it a real star-like object. We can also exclude a glint of a satellite (for example a Molniya satellite, i.e. with an inclination larger than 60°) because the image is not trailed in spite of being exposed for 300 s, as seen is many of the BOOTES database images. Moreover, a search on satellite databases has given negative results. During this time frame, within 0.5 degrees of this position, there was only one satellite, namely NORAD No. 14 473, this is a small piece of debris of a rocket launch with a radar cross section of 0.05 m^2. It appears on a track that remains at 0.5° away from the measured position of the OT and the track it follows in the sky never gets closer than 0.5 degrees. More importantly, this satellite is tiny, and is at a range of >3000 km. Even under full sun conditions, magnitude 10 is difficult to believe for this object. In reality, the orbit is deeply into the Earth's shadow, almost 1000 km. Under such conditions, only moon-light could reflect off of it, which renders it at least 13 mag fainter, and definitely fainter than mag 18. So, under no conditions can the optical transient be this satellite. There are no other known candidate satellites to explain it. In addition, the tiny angular extent of the observed optical signal (0.03°), tells that for this to be a satellite, it would have to have been an optical glint or flash of *very short* duration (<0.25 s). An airplane flash is ruled out as no other such event is detected in the full 16° × 11° field of view. We can also exclude a cosmic-ray (CR) mimicking an OT as the mean rate of CR in the BOOTES ST-8 CCD cameras is 0.1 min^{-1} cm^{-2}, i.e. 0.06 in a 300-s typical exposure. The probability of having a CR with a PSF similar to that of a star in the field is $\leq 10^{-2}$, thus this possibility can be significantly reduced ($P \leq 6 \times 10^{-4}$). A head-on meteor can be also ruled out, as it is extremely improbable, of order of $<10^{-6}$ (Hudec 1993; Varady & Hudec 1992). Moreover, the PSF analysis indicates no detectable trailing for the image.

4.2. A relationship to GRB 000313?

The OT 000313 is 23° from the center of the refined BATSE error box (the so-called Hunstville position). The statistical-only error radius is 7.6°, and the total error is best described by a two-component model, sum of two Gaussians (Briggs et al. 1999). Thus, the OT lies at 3.0σ from the center of the refined GRB 000313. The fact that this event was not detected by any other satellite resulted in the lack of a more accurate position from the high-energy data itself.

In the GRB fireball model the prompt optical flash seen in GRBs is thought to arise when a reverse shock propagates into the ejected shell (Sari & Piran 1999), whereas the afterglow emission that starts few minutes after the event is thought to be due to the forward shock propagating into the interstellar medium (ISM) after the shell has swept up a considerable volume of the ISM that surrounds the central engine (Mészáros & Rees 1997). If the OT 000313 is related to the GRB 000313 and we assume a power-law decay with the flux $F \propto t^{-\alpha}$ then, the derived power-law decay index is $\alpha \geq 2.2$, only comparable to the steepest GRB optical afterglows (Castro-Tirado et al. 2001). Figure 3 shows the light curve of the OT 000313 superimposed to the light curve of the GRB 990123 event for which a prompt optical flash was detected (Akerlof et al. 1999). The OT 000313 data are consistent with a fast decay similar to that of GRB 990123 ($\alpha = 2.1$, Akerlof et al. 1999) but with the absence of the optical afterglow (that started at about 0.01 day after the occurrence of GRB 990123). We can interpret this observational fact considering that only prompt optical emission has been detected in the OT 000313 but no optical afterglow emission at all. No radio afterglow emission was detected either (Berger & Frail 2000; Frail 2000), just like none has ever been found in other short, hard GRBs (Gorosabel et al. 2002; Hurley et al. 2002).

Although the origin of the long duration, soft GRBs seems to be widely accepted as the collapse of massive stars (Woosley 1993), the origin of the short duration, hard GRBs is still an open question. It has been proposed that the extremely brief bursts (<100 ms) might be due to primordial black hole (BH) evaporations (Hawking 1974; Cline et al. 1999) although most of the short, hard burst population is thought to be due to binary mergers (Narayan et al. 1992). Lifetimes of neutron

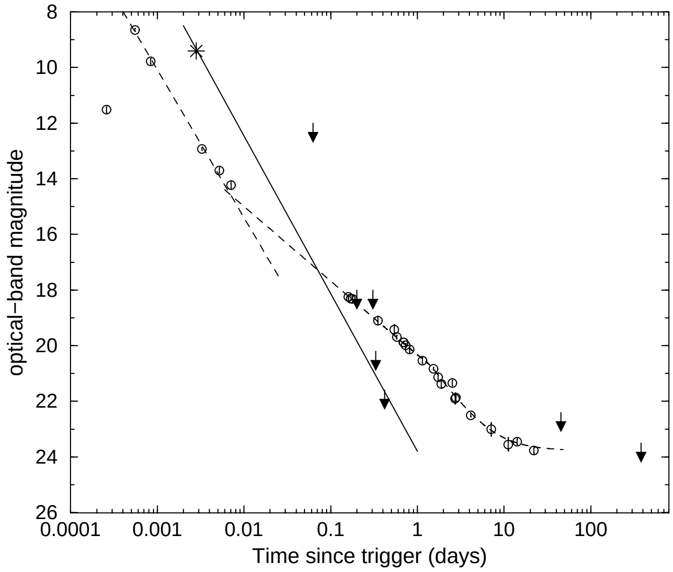

Fig. 3. The light curve of the OT 000313 (*I*-band, star, upper limits and solid line) superimposed to the light curve of the long-duration GRB 990123 (*R*-band, empty circles and dashed line), the only burst for which a prompt optical flash has been detected. The OT 000313 data are consistent with a prompt optical flash fast decay ($\alpha \geq 2.2$) comparable to that of the GRB 990123 ($\alpha = 2.1$) but with the absence of an optical afterglow (that started at about $T_0 + 0.01$ day in the GRB 990123). The GRB 990123 data are taken from Akerlof et al. (1999), Castro-Tirado et al. (1999b) and references therein.

star–neutron star (NS) systems are of the order of $\sim 10^9$ yr, and large escape velocities are usual, putting them far away from the regions where their progenitors were born. Therefore, the GRB progenitors in the binary merger model context would be located in very low density regions, where no afterglow emission is expected. The likely result is a Kerr black hole and the energy released during the merging process is $\sim 10^{54}$ erg, provided that the disk is sufficiently small and the accretion is driven by neutrino cooling (Narayan et al. 2001). In that case, the expected duration of the relativistic wind (i.e. the GRB) is $\sim$1 s. A similar "output" would be expected from a NS-BH merger (Paczyński 1991).

Theoretical models have recently claimed that short GRBs only could exhibit very faint optical afterglow emission ($R >$ 23, a few hours after the gamma-ray event, Panaitescu et al. 2001), therefore consistent with our upper limits. Although most NS–NS mergers should take place within a few tens of kpc from their host galaxies (see Fig. 21 of Fryer et al. 1999 for a range of masses of galaxies), the fact that no host galaxy is found within the error circle down to the above mentioned upper limits is not unusual, due to the fact that most host galaxies are fainter than $R = 24$ ($R = 24.8$ is the median apparent magnitude, Djorgovski et al. 2001).

If the OT 000313 is related to the short GRB 000313 then, the fact that only prompt optical emission has been observed (and no optical afterglow emission) might explain the fact that no other optical counterpart for the short GRB class has been detected. These observational facts might indicate that short GRBs occur in a low-density medium, favouring the models that relate them to binary mergers in galactic haloes or in the intragalactic medium.

We however note that a low density medium also makes it difficult to produce a 9 mag optical flash by the reverse shock, unless the bulk Lorentz factor Γ of the shell would be very large due to one of the following reasons: i) the typical reverse shock frequency $\nu_m \propto \Gamma^2 n^{1/2}$ with n the density of the ISM in the surroundings of the GRB. A small n requires a large Γ ($>10^2$) to make the spectrum peaking at optical (Kobayashi 2000); ii) $F_{\nu,\max}$ also positively related with n, Γ and the isotropic energy release $E_{\rm iso}$. For short bursts, if both n and $E_{\rm iso}$ are small compared with the long bursts, Γ should be very large to compensate the deficit; iii) to achieve a bright optical flash, the shell should be either thin ($\Delta_0 < l/\Gamma^{8/3}$ with Δ_0 the width of the shell and l the Sedov length i.e., the reverse shock would be not relativistic) or rather marginal (even better, i.e. the ratio $l/2\Delta_0\Gamma^{8/3} \sim 1$).

5. Conclusions

If the OT 000313 is indeed related to the short GRB 000313 then, the fact that only prompt optical emission has been observed (and no optical afterglow emission) might explain the fact that no other optical counterparts for the short GRB class has been detected, favouring the models that relate them to binary mergers in galactic haloes or in the intragalactic medium. Given the fact that the distance distribution of NS-NS mergers depends on the mass of the host galaxy (Fryer et al. 1999), deeper observations of the OT 000313 error box might help to better constraint the distance and/or the mass of the host galaxy.

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