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LETTER

Letter to the Editor

Early detection of the optical counterpart to GRB 980329[⋆,⋆⋆,⋆⋆⋆]

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Abstract. We report optical observations of the GRB 980329 error box which represent the second earliest detection of the GRB 980329 optical transient. We determine R = 23.7 ± 0.5 mag on 29.89 March, which is consistent with R = 23.6 ± 0.2 mag as reported by Palazzi et al. (1998) on 29.99 March. Based on extrapolations of the light curve we claim that the R-band magnitude of the GRB 980329 host galaxy should lie in the range 26.8 mag $<$ R $<$ 29 mag. We also discuss the similarities with GRB 970111.

Key words: methods: observational – gamma rays: bursts

1. Introduction

The Gamma-Ray Burst Monitor (GBM) on board the X-ray satellite *BSAX* was triggered by a gamma-ray burst (GRB) on 29 March 1997, UT 3 h 44 m 30 s and localised by the Wide Field Camera (WFC) on *BSAX* at $\alpha_{2000} = 7^h02^m41^s, \delta_{2000} = 38^\circ 50' 42''$ (uncertainty $3'$ radius). GRB 980329 was very intense and reached a peak intensity of 6 Crab in the 2–26 keV range, being the second brightest burst localised so far with the WFCs (Frontera et al. 1998). The event was also detected by the burst and transient source experiment (BATSE) on board the *Compton Gamma-Ray Observatory*, which provided a position consistent with the one given by the WFC (Briggs et al. 1998). A follow-up observation was initiated within 7 hr with the *BSAX* narrow-field instruments (NFI). The observation revealed a previously unknown X-ray source, 1SAX J0702.6+3850, that faded by a factor of ~ 3 over 14 hr of observation (in´t Zand et al. 1998). Radio observations performed with the VLA at 8.4 GHz resulted in the detection of a variable radio counterpart that peaked ~ 3 days after the burst (Taylor et al. 1998a,b). This detection allowed observers to re-examine images taken on the first night after the gamma event. Thus, observations at the position of the radio counterpart revealed a fading source in the I- (Klose 1998), R- (Palazzi et al. 1998, Pedersen et al. 1998), and K-bands (Larkin et al. 1998a,b; Metzger 1998) as well as in submillimetre wavelengths (Smith & Tilanus 1998a,b).

The data provided by the Interplanetary Network (IPN) allowed to derive an annulus that intersected the WFC error and reduced its area (Hurley et al. 1998). The new error box included the 1SAX J0702.6+3850 X-ray source, the variable radio source and the optical transient (OT). Deep optical observations revealed a faint galaxy (R $= 25.7 \pm 0.3$ mag) coincident to the optical fading source (Djorgovski et al. 1998), that was pointed out as the GRB 980329 host galaxy. Here we present the result of the optical observations performed at several observatories.

2. Observations and data analysis

Optical images in the R and B bands were acquired with three telescopes, namely the 1.5-m OAN at the German-Spanish Observatorio de Calar Alto, the 1.0-m JKT at Observatorio del Roque de los Muchachos and the 1.0-m OGS telescope at Observatorio de Izaña.

The 1.5-m OAN telescope is located at Calar Alto and its CCD provides a field of view (FOV) of $6'.9 \times 6'.9$. The 1-m JKT telescope, placed at La Palma, gives a FOV of $5'.6 \times 5'.6$. The

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⋆ Based on observations carried out at the 1.0-m Jacobus Kapteyn Telescope operated by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

⋆⋆ Based on observations carried out at the 1.5-m Telescope of the Observatorio Astronómico Nacional in Calar Alto.

⋆⋆⋆ Based on observations carried out at the 1.0-m Optical Ground Station telescope of the European Space Agency in the Spanish Observatorio del Teide of the Instituto de Astrofísica de Canarias.

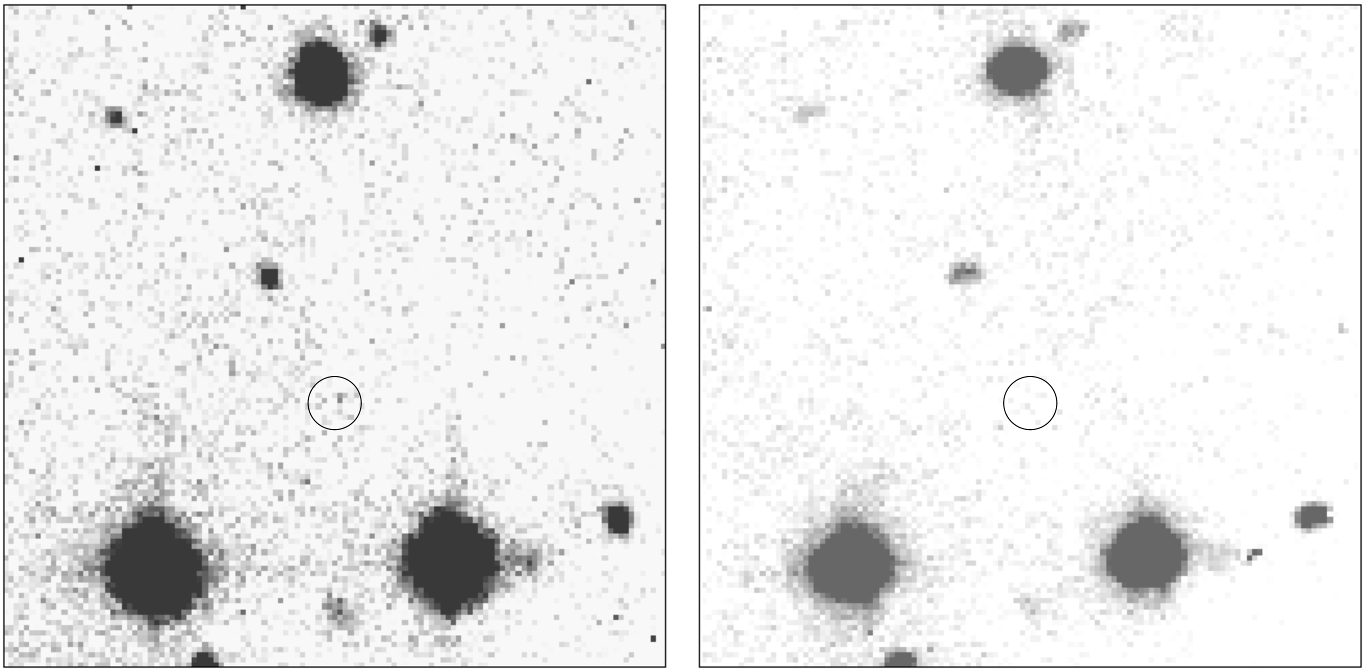

Fig. 1. The image shows the two R-band images of GRB 980329 taken with the JKT telescope; on 29.89 March (*left*) and the co-added image on 31.94 March. (*right*). The long integration times of 2700 s and 3600 s allowed to reach 3σ limiting magnitudes of R = 22.8 mag and 23.0 mag respectively. The faint object present at the radio counterpart position (circle), is not detected in the image taken on 31.94 March. The FOV is $38'' \times 38''$, with north is to the top and east to the left.

Table 1. Log of optical observations covering the GRB 980329 error box

Date of 1998 (starting time)	Filter	Exposure time (s)	Telescope	Limiting mag. (3σ)
29.85 Mar	R	900	1.0-m OGS	R=22.2
29.89 Mar	R	2700	1.0-m JKT	R=22.8
30.88 Mar	R	2700	1.0-m JKT	R=20.3*
31.00 Mar	R	1800	1.5-m OAN	R=20.8*
31.83 Mar	R	3600	1.5-m OAN	R=21.2*
31.93 Mar	R	1800	1.0-m JKT	R=22.8
31.96 Mar	R	1800	1.0-m JKT	R=22.8
2.89 Apr	R	7200	1.5-m OAN	R=21.5*
2.98 Apr	B	2400	1.5-m OAN	B=20.5*

* Observations carried out in bad weather conditions (clouds).

European Space Agency OGS is a 1-m telescope at the Observatorio del Teide. Its camera provides a $5'.1 \times 5'.1$ FOV. All three telescopes are equipped with a 1024×1024 pixel CCD. Table 1 displays the log of the performed observations for GRB 980329. The images were debiased and flat-fielded in the standard way using the IRAF reduction package. Magnitudes for the OT and for other objects in the field were obtained using the SExtractor software based on the corrected isophotal magnitude, which is very useful for star-like objects (Bertin and Arnouts 1996). In order to compare the magnitude of the object with others R-band measurements available on 29–30 March, we made use of the local standard considered by Palazzi et al. (1998), who on 29.99 March reported R = 23.6 $\pm$ 0.2 mag for the OT. This star is located at $\alpha_{2000} = 7^h2^m39.40^s$, $\delta_{2000} = 38°50'3.1''$, and has a magnitude R = 18.29 $\pm$ 0.05 mag (Palazzi 1998). It has to be pointed out that this calibration is systematically shifted 0.15 mag with respect to the one reported by Rhoads et al. (1998).

The images taken with both the 1.0-m OGS and 1.5-m OAN telescopes did not reveal the counterpart. However, the JKT image taken on 29.89 March shows the presence of a faint object located at the position of the radio and optical GRB counterparts (Taylor et al. 1998b, Klose 1998). See Fig. 1. Astrometry of the object was carried out by means of 15 stars in the image whose coordinates were taken from the USNO-A2.0 catalogue. Thus we obtain $\alpha_{2000} = 7^h2^m38.02^s \pm 0.05^s$, $\delta_{2000} = 38°50'44.2'' \pm 0.6''$ for the counterpart, which is $< 0''.5$ away from the position of the radio counterpart. The magnitude of the OT at this time was R = 23.7 $\pm$ 0.5 mag.

Our detection on 29.89 March is the second earliest optical detection of GRB 980329, corresponding the earliest one to the I-band detection by Klose (1998). As it can be seen on Fig. 2, this value is consistent with the measurements reported by other authors, namely R = 23.6 $\pm$ 0.2 mag on 29.99 March, R = 25.2 $\pm$ 0.3 mag on 1.125 April (Palazzi et al. 1998) and R = 25.7 $\pm$ 0.3 mag on 2.0 April (Djorgovski et al. 1998).

3. Discussion

3.1. Reliability of the object

A quantitative evaluation of the confidence level of our 2σ detection by means of SExtractor is done following two methods.

First, we considered the peak to peak signal-to-noise ratio, resulting that the peak intensity of the object is 4.5σ above the background level. On the other hand, aperture photometry measurements for the object and for several random points in the surrounding area were obtained by means of a FORTRAN code developed by us. Then, we calculated the confidence level in the same way as we did for the first case but using the integrated fluxes instead of the peak intensities. When aperture photometry of the object was carried out considering radii ranging from 3 to 6 pixels, the confidence level of the detection lies in the 3.4–2.0σ range. As expected, enhancing the aperture makes the background to come in, impoverishing the signal-to-noise ratio. The peak signal-to-noise ratio only takes into account the maximum value of the photodensity profile, so usually it will be larger than the one obtained with the aperture photometry.

The OT magnitude and the 3σ limiting magnitudes displayed in Table 1 have been calculated considering the most unfavourable case of a 6 pixels radius, where the detection of the object is at a 2.0σ level. This fact explains why the magnitude of the object is below the quoted 3σ limiting magnitude of R = 22.8 mag. If a gaussian fit is made to the object photodensity profile, we obtain a full width at half maximum (FWHM) of 3 pixels (or 1$''$), which is the typical value of the seeing derived for other objects in the field. On the basis of the confidence levels obtained, we consider the detection as *real*.

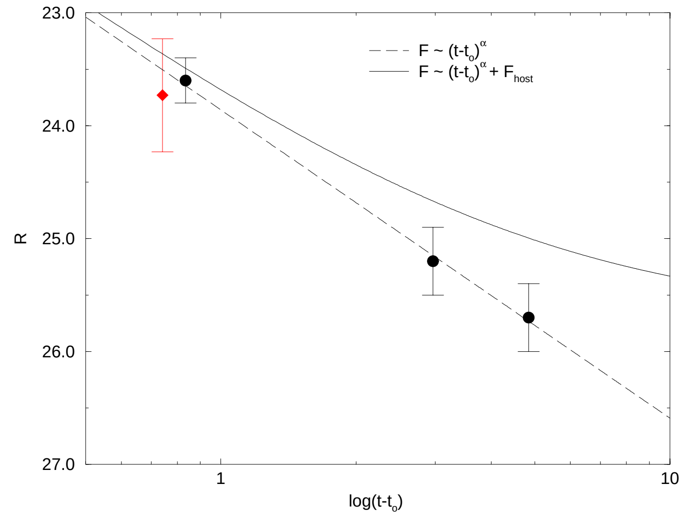

Fig. 2. The R-band light curve of the GRB 980329 counterpart. The diamond represents our detection on 29.89 March (R = 23.7 $\pm$ 0.5 mag), and the circles are the values reported elsewhere, namely R = 23.6 $\pm$ 0.2 mag on 29.99 March, R = 25.2 $\pm$ 0.3 mag on 1.125 April (Palazzi et al. 1998b), and R = 25.7 $\pm$ 0.3 mag on 2.0 April (Djorgovski et al. 1998c). The observed flux F is very well fitted by a power law in the form; $F \sim (t - t_o)^\alpha$ (long dashed line) with $\alpha = -1.1 \pm 0.4$. If we consider the contribution of a host galaxy $F_{\rm host}$ with R = 25.7 mag, the fit is not so good. This suggests that *still* on 2.0 April the OT contributes to a large fraction of the optical flux, while the contribution of the host galaxy is negligible.

3.2. Estimation of the magnitude of the host galaxy

By fitting a power law to the observed flux $F \sim (t - t_o)^\alpha$ we obtain an index $\alpha = -1.1 \pm 0.4$. The value of the reduced-chi-squared χ^2/dof for the fit is $\chi^2/dof = 0.15$, where dof is the number of degrees of freedom. We note that the low value of the reduced-chi-squared is due to the fact that the errors in the data points have been overestimated. This value is in agreement with the one given by Palazzi et al. (1998), who obtained $\alpha = -1.3 \pm 0.2$.

As it can be seen in Fig. 2, the expected light curve for a R = 25.7 mag host galaxy (Djorgovski et al. 1998) does not match well the observed flux. This suggests that the total optical flux was still dominated by the contribution of the OT when its magnitude was R = 25.7 mag on 2.0 April. In fact, if we extrapolate a single power law decay from the first three points to the one of 2.0 April, a value of R = 25.8 mag is obtained for the OT. This value is consistent, within the uncertainties, with the value measured at that date (R = 25.7 $\pm$ 0.3 mag).

If we consider now the contribution of the host galaxy to the observed flux $F = F_{\rm host} + B(t - t_o)^\alpha$, we can estimate the magnitude of the host galaxy. The values of χ^2/dof exhibits a broad minimum around R = 27.4 mag and so we conclude that the magnitude of the GRB 980329 host galaxy should lie in the range given by 26.8 mag $<$ R $<$ 29 mag.

3.3. Similarities between GRB 980329 and GRB 970111

GRB 970111 and GRB 980329 are two of the most intense GRBs detected by *BSAX*, showing prominent emission above 40 keV. In fact, their fluence in the 50–300 keV range is more than four times larger than the other GRBs detected (with the exception of GRB 990123). On the other hand, they displayed the hardest spectra, showing a hardness ratio (HR) between 0.5$\pm$0.2 and 1.0$\pm$0.2 (in´t Zand et al. 1998). Therefore, at first sight one could speculate that both GRBs were originated under similar physical conditions and nearer than the other GRBs of the *BSAX* sample.

If this was the case, the optical decay curves should be somehow similar. This fact could give us a clue for explaining the non detectability of GRB 970111 OT $\sim$19 hr after the gamma-ray event (Castro–Tirado et al. 1997). Assuming a similar decay trend and apparent magnitude for GRB 970111 than those of GRB 980329, the magnitude of the GRB 970111 OT 19 hr after the high energy event would be R $\sim$ 23.5 mag, just below the detection limit of our images taken on 20 Jan, 1997 (Gorosabel et al. 1998).

It could be possible that both GRBs were originated from a host galaxy at $z < 1$, a nearby source in comparison to the other *BSAX* GRBs for which redshifts has been measured. In fact, Palazzi et al. (1998) have suggested that GRB 980329 could be arised from a strongly obscured starburst galaxy at $z \sim 1$.

This statement could be supported if a correlation between the γ-ray flux and distance of GRBs is present. However, such a correlation has not been detected among the BSAX GRBs sample. Furthermore, it is in contradiction to the photometric redshift estimation of Fruchter (1999), who proposes that GRB 980329 host galaxy is at $z \sim 5$.

4. Conclusion

We present the optical follow up observations performed for GRB 980329 by means of the data acquired at the OGS, OAN and JKT telescopes. Only the image taken on 29.89 March with the JKT telescope reveals an object within $0\farcs5$ from the OT and radio positions. The magnitude of the OT on 29.89 March was R = 23.7 $\pm$ 0.5 mag, which is consistent with R = 23.5 $\pm$ 0.2 mag on 29.99 March, reported by Palazzi et al. (1998).

Based on extrapolations of the light curve we claim that the R-band magnitude of the GRB 980329 host galaxy should lie in the range 26.8 mag $<$ R $<$ 29 mag, considerably fainter as claimed by Djorgovski et al. 1998. This prediction should be tested with deep ground-based or *HST* observations.

GRB 980329 shows similar characteristics to GRB 970111. Assuming a similar decay trend and apparent magnitude, the OT associated to GRB 970111 19 hr after the high-energy event would be R $\sim$ 23.5 mag, just below the detection limit of our data. This fact could explain the non-detection of the GRB 970111 OT.

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