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Early detection of the Optical Transient following the Gamma–Ray Burst GRB 970228*

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Abstract. The optical counterpart of the Gamma–Ray Burst GRB 970228, discovered by Groot et al. (1997a), is also detected in the B and R frames obtained ∼4 hours earlier at the Bologna Observatory. Our observations indicate a very likely rise of the optical emission within these 4 hours. The R luminosity of the transient at maximum was about 15 times that of an underlying extended object. Follow–up data show that the maximum optical emission was delayed of not less than 0.7 days with respect to the γ–ray peak and that no new big flares were seen after the main one. The optical transient became significantly redder once it has reverted to quiescence.

Key words: Gamma rays: bursts — Methods: observational

1. Introduction

Gamma–Ray Bursts are strong high–energy flashes lasting a few seconds on average and showing an isotropic sky distribution (Fishman & Meegan 1995). Their emission in the other parts of electromagnetic spectrum is very elusive. Their distance is currently unknown, since no optical or radio counterpart has been detected so far. This situation seems to be rapidly changing thanks to the reduced error boxes now available. Therefore, it is of paramount importance to observe the error boxes of these bursts in the optical bands as soon as possible after the event, in order to catch the afterglow proposed by several theories. GRB 970228 offered for the first time the possibility of searching for an optical event shortly after a burst and to follow its evolution. Indeed an Optical Transient (OT) was suggested (Groot et al. 1997a, van Paradijs et al. 1997) as the optical counterpart of this Gamma–Ray Burst.

GRB 970228 was detected on February 28, 1997, by the X–ray satellite BeppoSAX (Costa et al. 1997a) as a four–peaked γ–ray burst at $\alpha = 5^{\rm h}01^{\rm m}57^{\rm s}$, $\delta = 11°46'.4$ (equinox 2000.0; error box radius = 3'), with total duration 80 seconds. Eight hours after the event, Costa et al. (1997b) observed a transient X–ray source, now labelled as SAX J0501.7+1146, located at the edge of the GRB 970228 error box. Palmer et al. (1997), Matz et al. (1997) and Liang et al. (1997) analyzed the spectral and the decay behaviours of both GRB 970228 and SAX J0501.7+1146; in particular, it was found that the γ–ray spectrum was consistent with that of a classical burst. Preliminary comparison with the Digital Sky Survey showed no brightening of sources to $V = 19$ (Groot et al. 1997b), $B = 19$ and $R = 20$ (Guarnieri et al. 1997). Hurley et al. (1997), using the Ulysses satellite data, reduced the error box of GRB 970228 and found that the SAX J0501.7+1146 error box overlapped partially that of the γ–ray burst. Within the intersection of the former error boxes Groot et al. (1997a) discovered an OT, which they indicated as probably related to GRB 970228. A thorough presentation of this result was given by van Paradijs et al. (1997).

In this paper we present the optical photometric analysis of the error box of GRB 970228, started ∼17 hours after the gamma–ray event, from February 28 to March 18, 1997. Section 2 will present the data along with the reduction and calibration techniques, while Sect. 3 will discuss the results. Finally, Sect. 4 will draw the conclusions.

* Based on observations obtained at the Osservatorio Astronomico di Loiano, Italy

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Table 1. Measured B and R magnitudes of the OT, possible counterpart of GRB 970228, plus the nearby red star and the extended object. The dates are computed at the times of mid–exposure

Day of 1997 (UT) at mid–exposure	Band	Magnitude	Exposure time (seconds)
Feb. 28.827	R	21.1 ± 0.2	1800
Feb. 28.861	B	22.3 ± 0.3	3600
Mar. 1.791	R	>21.4	1600
Mar. 3.764	R	22.3 ± 0.5	1800
Mar. 4.791	R	22.2 ± 0.5	1800
Mar. 4.853	B	>22.5	3600
Mar. 5.858	R	>22.2	1800
Mar. 12.802	R	22.6 ± 0.5	1800
Mar. 12.843	B	>22.4	3600
Mar. 13.817	B	>21.5	3600
Mar. 13.852	R	>22.3	1800
Mar. 18.815	R	>20.6	2400

2. Observations and analysis

We started an optical observational campaign on the GRB 970228 error box in order to search for possible optical counterparts of the γ–ray event, beginning 15.5 hours after the burst (Guarnieri et al. 1997). Owing to the large initial error box (15' in radius; Costa & Frontera 1997) it was not possible to cover it with a single CCD frame; we succeeded to locate the "right" field ~16.5 hours after the event, i.e. on February 28.816 UT.

The frames were obtained with the 1.5-meter telescope of the Bologna University equipped with the BFOSC instrumentation (Merighi et al. 1994), which allows fast switching from the spectrographic to the imaging mode. Images have a scale of about 0.5 arcsec pixel^{-1}. The field was observed on February 28 and on March 1, 3, 4, 5, 12, 13 and 18, 1997. R and B filters were employed, with exposure times spanning from 30 to 60 minutes. The limiting magnitude strongly depended on the seeing and on the sky conditions, which were fairly good on February 28, March 3, 4 and 12 (typical FWHM of the PSF: 4 pixels). On March 1, 5, 13 and 18 the bad seeing and poor sky conditions implied frames with a low signal–to–noise ratio; therefore, they gave us only lower limits for the magnitudes of the object.

B, V and R images of the Selected Area 101 (Landolt 1992) were also obtained on March 4 in order to calibrate the field of GRB 970228. After the standard cleaning procedure for bias and flat field, the frames were processed with the DAOPHOT II package (Stetson 1987) and the *ALLSTAR* procedure inside MIDAS. We used simple aperture photometry when the objects were too faint to be detected with DAOPHOT II. Then, the fields were calibrated with the standard stars quoted above.

We detected an OT at the intersection of the error boxes of GRB 970228 and SAX J0501.7+1146 with coordinates $\alpha = 5^{\rm h}01^{\rm m}47^{\rm s}$, $\delta = 11°46'55"$ (equinox 2000.0; error: ±5"). Its position makes it practically coincident with the proposed optical counterpart of GRB 970228. Its magnitude changed from $R = 21.1 \pm 0.2$ and $B = 22.3 \pm 0.3$ on February 28.8 UT to $R = 22.3 \pm 0.5$ on March 3.8 UT and $B > 22.5$ on March 4.8 UT. In the days following March 3.8 the R magnitude of the object seemed to remain more or less constant. Table 1 shows the measured B and R magnitudes. The reported values are the integrated magnitudes of the OT plus a nearby star and an extended object (van Paradijs et al. 1997). The latter is possibly the host of the OT, 0".2 away (van Paradijs et al. 1997, Groot et al. 1997c) and with $R = 24$ (Groot et al. 1997c, Metzger et al. 1997a), whereas the nearby object is an early M–type star (van Paradijs et al. 1997, Groot et al. 1997c) or a mid K-type star (Tonry et al. 1997), located 2".7 away, constant in brightness with $R = 22.4$ (Metzger et al. 1997a) and unrelated to the OT (Groot et al. 1997c). Due to the seeing conditions, we were not able to separate the OT from the star.

In our frames the red star is more likely responsible for the observed residual emission already since March 3. Actually, the R magnitude of the object after that day, within the errors, is the same as the red star located near the extended source as indicated by Metzger et al. (1997a). This means that the main optical effects of the γ–ray explosion (rise and first decay phase) developed before March 3.8. Indeed, observations made on March 6.3, 11.2 (Metzger et al. 1997a), 9.9 and 13.0 (Groot et al. 1997c) show that the underlying extended object is constant in brightness. Therefore, within the accuracy of the measurements, the time span of 3.6 days is the upper limit to the duration of the brightest phase of the point–like OT, as Table 1 shows. Our observations are consistent with the fading object found by Groot et al. (1997a) and van Paradijs et al. (1997) with $V = 21.3$ and $I = 20.6$ on March 1.0 UT and $V > 23.6$ and $I > 22.2$ on March 8.9 UT. According to van Paradijs et al. (1997) and Metzger et al. (1997a), it is ~0".2 from a quiescent object, which appears to be extended and therefore likely to be a galaxy which could be associated with the X–ray transient and, presumably, with the GRB.

We could now subtract from the total fluxes of the optical event those of the M–type star and of the extended object. Since the constant red star and the underlying extended object were always undetectable in our B band photometry, we can assume that the B magnitude on February 28.8 is representative of the transient event. We obtain $B = 22.4$ and $R = 21.6$, implying $B - R = 0.8$ as the color index of the OT ~17 hours after the γ–ray event. On March 3.8 we deduce that the OT was fainter than $R = 23$. Van Paradijs et al. (1997) report a fading $\Delta V > 2.9$ mag in the time interval March 1.0–March 4.9.

Table 2. X–ray, B, V (Johnson), R and I (Cousins) fluxes of the event. B and R values were computed by subtracting from the data of Table 1 in the days from February 28 to March 3 the fluxes of the extended object and of the nearby star. Effective wavelengths are reported. We adopted the band widths published by Fukugita et al. (1995). All fluxes are in units of 10^{-15} erg cm^{-2} s^{-1}. Data between parentheses are inferred from our interpolations. See text for further details

Day of 1997 UT	X–ray flux 0.5 – 10 keV	B flux $\lambda = 4448$ Å	V flux $\lambda = 5505$ Å	R flux $\lambda = 6588$ Å	I flux $\lambda = 8060$ Å	Reference number
Feb. 28.46	4000	—	—	—	—	1
Feb. 28.827	—	5.7 ± 2.5	(4.4 ± 2.4)	7.7 ± 2.4	—	2
Feb. 28.99	—	—	9.0 ± 0.9	(14.1 ± 1.9)	9.8 ± 1.0	2,3,4
Mar. 1.79	—	—	—	<5.8	—	2
Mar. 3.73	200	—	—	—	—	1
Mar. 3.76	—	—	—	<2.4	—	2
Mar. 4.86	—	—	<0.6	—	—	4
Mar. 8.9	—	—	<1.1	—	<2.3	3,4
Mar. 26.4	—	—	0.11 ± 0.01	(0.27 ± 0.03)	0.36 ± 0.04	2,5
Apr. 7.2	—	—	0.08 ± 0.01	(0.20 ± 0.03)	0.25 ± 0.02	2,5

Refs. — 1. Costa et al. 1997b; 2. this work; 3. Groot et al. 1997a; 4. van Paradijs et al. 1997; 5. Sahu et al. 1997.

Pedichini et al. (1997) observed a fading of 2.7 mag between February 28.8 and March 4.8.

3. Discussion

The combination of Bologna ($B = 22.4 \pm 0.4$, $R = 21.6 \pm 0.3$; this work) and La Palma ($V = 21.3 \pm 0.1$, $I = 20.6 \pm 0.1$; van Paradijs et al. 1997) data taken on February 28 could provide very important informations to understand the nature of this transient, so far unique in the optical bands. These observations are not simultaneous, therefore they can give some insights into the problem of the light variation and into the related one of the energy distribution. We consider here three different hypotheses: a) the brightness was constant during the four hours between the two sets of observations, one obtains $B - V = 1.1$, $V - R = -0.3$, and $R - I = 1.0$; such color indices are not consistent with the spectral energy distribution of any known astrophysical object and imply strong variations with the wavelength. b) a fading during the time span between Bologna and La Palma observations; in this case the above result would be strengthened. c) the possibility of an increasing emission. In the latter case, we can interpolate the V spectral flux density from B and R values at the time of the Bologna observations. We assume tentatively a linear flux density $\Delta F/\Delta\lambda$ distribution. The conversion from magnitudes to fluxes was done using Table 9 by Fukugita et al. (1995). We obtain 5.9×10^{-18} erg cm^{-2} s^{-1} Å^{-1}, corresponding to $V = 22.0$. In the same way, from La Palma V and I magnitudes we derive a R spectral flux density of 9.0×10^{-18} erg cm^{-2} s^{-1} Å^{-1}, which gives $R = 20.9$. Thus, the total R flux at maximum was not less than 15 times that of the extended object. These figures imply a flux increase of 1.9 times in V and R between the two sets of observations, corresponding to a variation of -0.7 mag in both bands, with a mean rate of ~ -0.2 mag hr^{-1}. The conclusion seems to be inescapable: either the OT has a very bizarre spectrum, or if it has a more normal spectral distribution it must display an increase of brightness between Bologna and La Palma observations. In the framework of the foregoing hypothesis, this result is significant at a 2σ confidence level. Being cautious for the observational error, we suggest that the optical luminosity increased at least until March 1.0 UT. Indeed a quick computation shows that, in order to have constancy or a decrease in brightness with a 3σ confidence level between Bologna and La Palma data, we should have observed the OT at least at $R = 20.5$ on February 28.8; this value is outside the 3σ interval centered on the observed magnitude $R = 21.6 \pm 0.3$. We then conclude that the hypothesis of a non–increase in brightness can be rejected with a confidence level of almost 4σ.

We can now refine our first–approximation figures. On February 28, the Bologna B value was acquired about 50 minutes later than the R one, therefore we might infer that the B magnitude of the OT at the time of the R frame was actually brighter by $\sim$0.2 mag. This implies a simultaneous $B - R$ color index of $\sim$1.0; correspondingly, one has $B = 22.6$ and $V = 22.1$ (interpolated at the same time). Bearing this in mind, it results that in a time span of about 4 hours the V magnitude of the OT decreased of 0.8 mag; this corresponds to a flux increase of a factor $\sim$2.1.

HST data (Sahu et al. 1997) are particularly relevant for understanding the mid–term behaviour of the OT. Therefore, by using the method described above, we computed the R flux densities and magnitudes; we obtained $R = 25.2$ for March 26 and $R = 25.6$ for April 7. From these data it is evident a substantial reddening of the OT, which changed from $V-R = 0.4$ and $V-I = 0.7$ on February 28.99 to $V-R = 0.9$ and $V-I = 1.9$ on March 26.4. The fluxes corresponding to these interpolations, together with those of other relevant B, V, R and I measurements and with the fluxes of the X–ray transient source SAX J0501.7+1146 given by Costa et al. (1997b) are reported in Table 2.

In spite of the poor quality of our observation of March 1.8 UT we can state that, on the basis of a comparison with other objects in the frame, at that time the OT had faded below the level of our first detection. Therefore we can fix the time delay τ_d between the γ–ray event and optical maximum in the range $0^{\rm d}.71 < \tau_d < 1^{\rm d}.67$. Correspondingly, the duration τ_f of the first fading phase is $\tau_f < 2^{\rm d}.93$. During this time the fading rate is ≈1 mag day^{-1}. This fixes tight constraints on both the rising and fading optical rates. The presence of an early phase of rapid fading is implicitly confirmed by the R band observations of Metzger et al. (1997a,b) who found that the total R magnitude has slowly faded by 1.0 ± 0.4 mag in one month (March 6–April 6).

If we assume for the R band luminosity a power law decay $L_{{\rm opt}(R)} \propto t^{-\alpha}$, a limit $\alpha > 1.1$ can be determined by using the R flux (interpolated as before) from the HST data of March 26.4 (Sahu et al. 1997); the optical data of the first days require $\alpha > 1.4$. An index $\alpha \sim 1.4$ is also found for the X–ray decay behaviour. An exponential decay law, similar to that of X–ray bursts, results in a decay time $<1^{\rm d}.3$, to be compared with $\sim 1^{\rm d}$ deduced by Palmer et al. (1997) for the X–ray emission. The ratio $L_{{\rm opt}(R)}/L_{{\rm X}(0.5-10~{\rm keV})}$ is $\approx 4\times10^{-3}$, if the luminosity values are taken at their respective observed maxima (at least 13 hours apart). By scaling the X–ray flux at the time of optical maximum (with a $1^{\rm d}$ decay law), we obtain $L_{{\rm opt}(R)}/L_{\rm X} \approx 6\times10^{-3}$. On March 3 X–ray and optical observations were nearly simultaneous: we can fix an upper limit of $\approx 1.2\times10^{-2}$ to the $L_{{\rm opt}(R)}/L_{\rm X}$ ratio.

It is interesting to note that Castro–Tirado et al. (1997) did not see anything noteworthy in the error box of another Gamma–Ray Burst, GRB 970111, just 19 hours after the γ–ray event. This indicates a significant difference in the optical behaviour of GRB 970111 and GRB 970228.

4. Conclusions

We can now summarize the main results of this work:

1. our observations in B and R bands, probably the earliest to the GRB 970228 event, clearly reveal the fading object (Groot et al. 1997a, van Paradijs et al. 1997) in the intersection of the combined error boxes of GRB 970228 and SAX J0501.7+1146;
2. they also indicate an increase in luminosity of a factor ∼2 on a time scale of 4 hours;
3. the bulk of the optical event (rising and first decay phase) developed in no more than $3^{\rm d}.6$;
4. the maximum of the optical emission from the 'fireball' was attained probably not earlier than $0^{\rm d}.71$ after the γ–ray burst;
5. the ratio $L_{{\rm opt}(R)}/L_{{\rm X}(0.5-10~{\rm keV})}$ at the supposed optical maximum is $\approx 6\times10^{-3}$;
6. the R luminosity of the OT at maximum is about 15 times that of the underlying extended object;
7. our sampling of the source until March 18 shows that after the first there were no new big flares;
8. the color indices significantly reddened during the month after February 28.

In conclusion, if the optical fading object is the counterpart of GRB 970228, all this severely constrains the modeling of Gamma–Ray Bursts.

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Note added in proof. The proposed optical counterpart of GRB 970508 confirms the existence of a significant time delay between the γ–burst and the maximum of optical brightness, as shown in this work.

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