SEARCH FOR OPTICAL COUNTERPARTS OF GRB SOURCES AT THE BOLOGNA ASTRONOMICAL OBSERVATORY

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ABSTRACT. B, V and R optical photometry performed on the fields of the GRBs 970111, 970228 and 970508 soon after their detection by BeppoSAX is presented. The Optical Transients (OTs) associated to the last two GRBs were found; these were the first cases in which the optical counterpart to a GRB was detected and followed in its decay. No remarkable optical object was instead found inside the corrected error box of GRB 970111. The optical counterpart of an X–ray and radio source and a suspected red variable (probably an eclipsing binary) have been detected in the field of GRB 970111.

1. Introduction

After repeated attempts of the international astronomical community to identify the optical counterparts of the Gamma–Ray Burst (GRB) sources, the launch of the Italian–Dutch satellite BeppoSAX (Boella et al. 1997) gave new chances of identification by providing error boxes small enough to try deep observations by the CCD cameras of medium–large telescopes within the very first hours from the onset of the burst, thus making ground–based optical observers able to catch a possible afterglow of the source in the visible light. This happened in March 1997, when the first Optical Transient (OT) associated to a GRB has been discovered in the form of a fading transient object imaged in the error box of GRB 970228 (Groot et al. 1997a, van Paradijs et al. 1997).

In this paper we present the results of the observational campaign carried on at the 1.5–meter telescope of the University of Bologna in Loiano on three GRBs detected by BeppoSAX, i.e. GRB 970111, GRB 970228 and GRB 970508.

2. Observations and results

All the data were acquired with the 1.5–meter Loiano telescope equipped with the BFOSC instrumentation (Merighi et al. 1994), which allows fast switching from the spectrographic mode to the imaging mode.

The reduction of the data, after the standard cleaning procedure for bias and flat field, was performed by processing the frames with the DAOPHOT II package (Stetson 1987) and the *ALLSTAR* procedure inside MIDAS. We used simple aperture photometry when the object were too faint to be detected with DAOPHOT II. In the case of GRB

TABLE I
Log of the observations performed on the field of GRB 970111 with the 1.5m Loiano telescope

Date of 1997	Filter	Number of frames	Exp. times (minutes)	Target
Jan. 14	B, R	1,1	20	GRB 970111
Jan. 17	B, R	1,2	45;15	GRB 970111 and source 'a'
Jan. 31	B, V, R	1,1,1	50;20;15	source 'a'
Feb. 14	R	1	30	source 'a'
Feb. 17	V, R	1,1	45;30	source 'a'
Feb. 18	B, V, R	1,1,2	75;45;30	source 'a'
Mar. 5	R	3	30	GRB 970111 and source 'a'
Mar. 13	B, R	2,2	60;30	source 'a'

970508 the analysis has been carried out with the IRAF package. All the relevant fields were calibrated using standard stars (Landolt 1992).

The next Subsections will report the main results achieved in the analysis of the error box of each one of the three GRBs reported above.

2.1. GRB 970111

GRB 970111 was detected on January 11 (Costa et al. 1997a). Soon after, Butler et al. (1997) reported that two faint X–ray sources, hereafter labelled as 'a' and 'b', were present in the field of GRB 970111. According to Guarnieri et al. (1997a), no object showed remarkable variations in the optical, neither in the error boxes of the two X–ray sources nor in the remaining part of the field of GRB 970111. Then, Hurley et al. (1997a) reduced the error box of GRB 970111 and found that only BeppoSAX source 'a' lied within it. Source 'a' appeared to be also a radio source (Frail et al. 1997a). The width of the error box did not allow us to image it in one single frame, so we focused our attention on the locations of the X–ray sources, particularly source 'a'. Unfortunately, due to a misalignment of the Wide Field Cameras of BeppoSAX (in't Zand et al. 1997), the error box reported by Costa et al. (1997a) had to be shifted of ~3' from its previous position; Hurley et al. (1997b) then gave a new error box, seven times smaller than the former and located in its southern part.

We imaged the field of GRB 970111 from January 14 (i.e. ~65 hours after the γ burst) to March 13. The journal of the observations, also reporting the target for each one of them, is shown in Table I.

The main results of the study of the GRB 970111 field are reported by Masetti et al. (1997). Here we briefly resume them. The analysis of the colors of all the objects inside the field and of their variability led to the conclusion that they showed neither any remarkable blue excess (we found that no $B - V$ was lower than 0.5 and no $V - R$ was lower than 0.2), nor a variation of more than 0.3 mag in R, thus confirming the results by Castro–Tirado et al. (1997a).

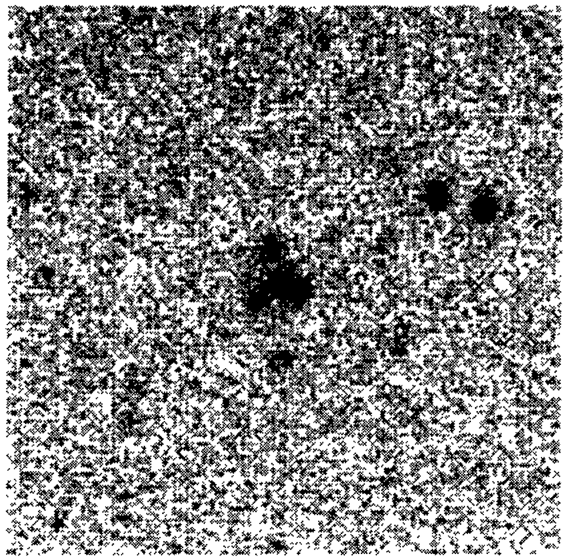

Fig. 1. Optical counterpart of the BeppoSAX X–ray source 'a' (Butler et al. 1997) and of the radio source VLA 1528.7+1945 (Frail et al. 1997a). The frame (exposure time: 30 minutes) was acquired in the R band on Mar. 5, 1997. North is at top, east is on the left. The field is $\sim$1'$\times$1'. Note the extended structure of the object, which is formed by at least two galaxies (Kulkarni et al. 1997).

Then, we identified the optical counterpart of BeppoSAX X–ray source 'a' (Butler et al. 1997) and of radio source VLA 1528.7+1945 (Frail et al. 1997a). This object has been resolved by Kulkarni et al. (1997) into two moderately redshifted galaxies separated by $\sim$2".5. Indeed, it is asymmetrical and seems to be formed by at least two (but probably four; see Fig. 1) objects, with the two brighter ones coinciding with the galaxies S1 and S2 reported by Kulkarni et al. (1997).

In the imaged field, at $\alpha = 15^{h}\ 28^{m}\ 45^{s} \pm 0^{s}.3$ and $\delta = +19^{\circ}$ 47' 15" $\pm$5" (equinox 2000.0), but outside the GRB error box, we also found a red variable with $R \sim 19.9$. The magnitudes and colors of this star (Masetti et al. 1997) seem to indicate it might be a long–term red variable (RV Tauri type, Mira or Semiregular); the hypothesis that the star undergoes eclipses with $\Delta R \sim 0.5$ and lasting less than three hours (as we observed on Feb. 18, 1997) however hardly agrees with the possibility that the variable is a giant star. Moreover, if we estimate the distance of the star from its absolute magnitude, ranging from 0 and -3 for a giant red variable, we obtain a value $> 10^5$ pc, which would place the object far outside our galaxy. Therefore we propose that the star is an eclipsing red dwarf caught at its primary maximum in the Palomar plate, while on the night of Feb. 18 it was probably observed at its secondary minimum.

2.2. GRB 970228

This GRB was detected on February 28.123, 1997, by BeppoSAX (Costa et al. 1997b). Eight hours after the event, Costa et al. (1997c) observed a transient X–ray source, now labelled as SAX J0501.7+1146, located at the edge of the GRB 970228 error box. Frail et al. (1997b) revealed the presence of a radio source near this X–ray object but likely not associated with it (Smith et al. 1997). On Mar. 9, Groot et al. (1997a; see also van Paradijs et al. 1997) discovered an OT inside the error boxes of the γ–ray and the X–ray sources. This was the first optical counterpart ever seen for a GRB after the γ event.

The Bologna observations (Guarnieri et al. 1997b) were however taken ~4 hours before the first detections by Groot et al. (1997a). Indeed we began the optical observational campaign on the GRB 970228 error box 15.5 hours after the burst, on Feb. 28.769. Owing the large initial error box (15' in radius; Costa & Frontera 1997), we pointed at the right field ~16.5 hours after the event, i.e. on Feb. 28.810.

In order to obtain a good quality photometry of relevant objects in the GRB 970228 field, which was observable only at large airmasses, we used the nightly extinction coefficients simultaneously obtained with another nearby telescope (about 200 meter apart) which was observing the Be–X system A0535+26, located approximately in the same zone of the sky.

We then observed the error box of GRB 790228 until Mar. 18. Our data (Guarnieri et al. 1997b) showed that the R light curve of the OT associated to GRB 970228 presented a rising branch with an increase in luminosity of a factor ~2, and that the light peak was achieved about one day after the γ event. Moreover, the bulk of the optical event (rising and first rapid decay phase) developed in no more than $3^d.6$, the ratio $L_{\rm opt(\it R)}/L_{\rm X(0.5-10\ keV)}$ at the supposed optical maximum was $\approx 6\times10^{-3}$ and the R luminosity of the OT at maximum was about 15 times that of the underlying extended object. The monitoring of the source in the following 18 days revealed that no new big flares were produced by the transient. The comparison of our data with those obtained with the HST (Sahu et al. 1997) showed that the color indices of the OT significantly reddened during the month after February 28.

For a more complete description of the work carried out with the data acquired in Loiano, see Guarnieri et al. (1997b).

In our images, a nearby 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. 1997b) is merged with the OT due to the seeing conditions, and we were not able to separate the OT from the star. Moreover, according to Groot et al. (1997b), a nebulosity with $R = 24$ is associated to the OT. We then subtracted these contributions to our R values and upper limits; after, we collected from Galama et al. (1997) the published R data and plotted the R light curve for the OT associated to GRB 970228. This light curve is shown in Fig. 2.

It can be noted that the main optical event lasted less than 4 days, with a power law decay index $\alpha_R > 2$; then, the luminosity of the OT faded more slowly with $\alpha_R < 0.6$. These figures are consistent with those of Galama et al. (1997).

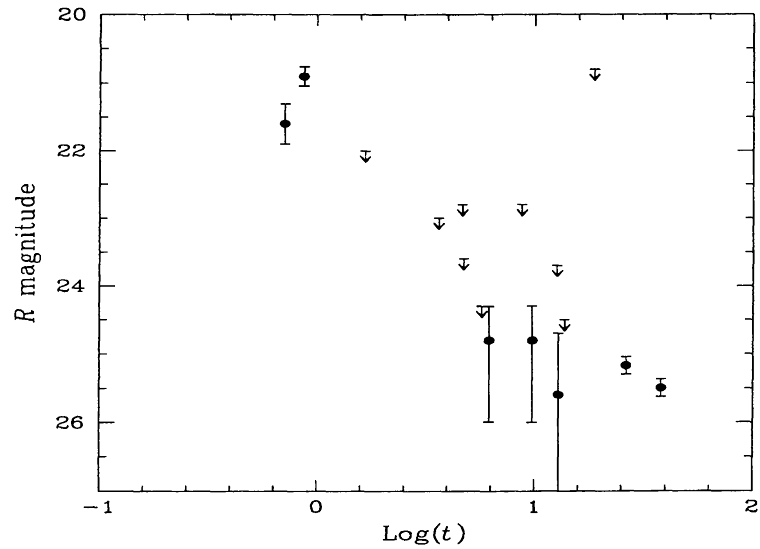

Fig. 2. R light curve of the OT associated to GRB 970228. Data and upper limits are from Galama et al. (1997) and Guarnieri et al. (1997b). t is the time elapsed from the onset of the γ event. Note the rise and the delayed light peak, achieved about one day after the γ burst. The decay seems to have a two–fold behaviour: very fast during the first 4 days from the light peak and remarkably slower afterwards.

2.3. GRB 970508

The OT associated to GRB 970508 was discovered by Bond (1997) as a starlike object few hours after the γ burst detected on May 8.904, 1997 (Costa et al. 1997d) and the discover of a fading X–ray emission (Piro et al. 1997) associated to the GRB. According to Castro–Tirado et al. (1997b), the object is very blue and starlike in shape during this phase.

Deeper imaging made by Schaefer et al. (1997) seemed to reveal the presence of a 'Z'–shaped nebulosity coincident with the OT, further resolved into two components (a red point source and an arc–like object) by Kopylov et al. (1997). Anyway, HST observations made on June 2, 1997, do not reveal any underlying nebulosity (Fruchter et al. 1997). Thus, the arc–like feature might have possibly faded during the decay phase. A power–law decay trend, with a spectral index $\alpha_{\rm opt} = 1.1$ (see e.g. Kopylov 1997 and Fruchter et al. 1997) was found for the luminosity of the OT.

Spectroscopic observations revealed a quite smooth continuum with the absence of obvious emission lines (Castro–Tirado et al. 1997b) and, most of all, the presence of Fe II, Mg II and [O II] absorption lines with redshift $z = 0.835$ (Metzger et al. 1997b). On May 13.96, nearly a week after the onset of the γ burst, Frail & Kulkarni (1997) found a flaring radio source, increasing in brightness, which was coincident with the positions

TABLE II
Log of the observations performed on the field of GRB 970508 with the 1.5m Loiano telescope

Date of 1997	Filter	Number of frames	Exp. times (minutes)	Magnitude
May 9.87	R	3	20	$R > 20.5$
May 10.85	R	4	20	$R = 19.78 \pm 0.05$
May 13.85	R	4	20	$R = 20.5 \pm 0.15$
May 14.86	R	3	20	$R = 21.5 \pm 0.2$
May 23.89	R	4	20	$R > 20.5$

of the X–ray and optical counterparts of GRB 970508.

This is the first detection of an optical redshift and of a radio counterpart associated to a GRB. The former would move the origin of at least part of the GRB sources to cosmologic distances, while the latter implies strong constraints on the theoretical model of GRBs.

The optical counterpart to GRB 970508 has been monitored with the Bologna 1.5–meter telescope in Loiano for nearly two weeks and it was clearly found in our data. Table II lists all the observations performed on GRB 970508 in Loiano.

As in the case of GRB 970228, the Loiano observations (Mignoli et al. 1997) revealed the presence of a rising branch. Indeed we note that on May 9.86 the OT was undetected ($R > 20.5$), while the day after, on May 10.85, it was at $R = 19.78 \pm 0.05$. Moreover, the OT was caught at or near its maximum on May 10.85. So, we can say that the OT associated to GRB 970508 peaked in the R band about two days after the γ detection. In the light of the behaviour of GRB 970228, this might be a common feature for GRB optical counterparts.

Images taken on May 13.85 and 14.86 showed the decay of the OT. Our data reasonably fit the power law trend indicated above. During all our observation runs, no variability was found among the frames obtained during the same night. For the R value of May 23.89 only an upper limit (>20.5; see Table II) could be given due to the extreme faintness of the OT at that time and to the poor seeing. Magnitudes were calibrated using the R values of field stars given by Schaefer et al. (1997).

Our data are now part of a larger work involving several astronomical institutes in an international network (see Castro–Tirado et al. 1997c).

3. Conclusion

The optical photometry performed with the 1.5–meter Loiano telescope on the fields of the GRBs 970111, 970228 and 970508 led to the detection of two OTs associated to GRB 970228 and GRB 970508 and gave fundamental information on the behaviour of OTs associated to GRBs in their early phases. In particular, we showed the unexpected presence of a rising branch in the light curves of both OTs.

No remarkable optical object was instead found inside the corrected error box of GRB 970111. Anyway, the optical counterpart of an X–ray and radio source and a suspected red variable (probably an eclipsing binary) have been detected during this work.

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