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*Letter to the Editor*

# ESO deep observations of the optical afterglow of GRB 990510*

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**Abstract.** We present the results of optical observations of the GRB 990510 field carried out at different epochs from European Southern Observatory (ESO) telescopes. Deep observations, down to a limiting magnitude of about 27 and 24 in the Bessel–$R$ and Gunn–$I$ band, respectively, were obtained between May 16 and 18 from the ESO NTT–SUSI2 telescope and on May 20 from the ESO 3.6 m (EFOSC2) telescope. These observations, together with other published photometric data, allowed to monitor the faint tail of the decaying Optical Transient (OT) associated to the GRB 990510. We discuss the light curves in the different filters ($V$, $R$ and $I$) in the light of the recently proposed decay laws. No obvious host associated to the GRB 990510 optical afterglow was found in the $R$ and $I$ band images. By comparing the light curves with respect to the theoretical colors of galaxies with different morphology we derived a lower limit of $R \sim 26.6$ for the host galaxy.

**Key words:** galaxies: general – galaxies: photometry – cosmology: observations – gamma rays: bursts

## 1. Introduction

On 1999 May 10.36743 UT the BATSE detectors on board CGRO, and the Gamma–Ray Burst Monitor (GRBM) and the Wide Field Cameras (WFCs) on board the Italian–Dutch satellite *Beppo*SAX detected a gamma ray burst, GRB 990510, with a fluence of $2.5{\times}10^{-5}$ erg cm$^{-2}$ above 20 keV (Kippen 1999; Amati et al. 1999; Dadina et al. 1999). The first optical follow–up observations began only ∼3.5 hours after the $\gamma$–ray event and revealed a relatively bright optical transient ($R$=17.54, Axelrod, Mould & Schmidt 1999; Vreeswijk et al. 1999a) at $\alpha = 13^{\rm h}38^{\rm m}07.11^{\rm s}$, $\delta = -80^\circ 29' 48.2''$ (equinox 2000; Hjorth et al. 1999b). When compared to previously studied afterglows, the OT showed initially a fairly slow flux decay ($\propto t^{-0.9}$; Galama et al. 1999), that steepened after one day ($F_\nu \propto t^{-1.3}$; Stanek et al. 1999a) and further steepened after 4 days ($F_\nu \propto t^{-1.8}$; Pietrzyński & Udalski 1999; Bloom et al. 1999) and 5 days ($F_\nu \propto t^{-2.5}$; Marconi et al. 1999a,b). Such a progressive and smooth steepening had not been observed before. Vreeswijk et al. (1999), using the VLT, detected red–shifted absorption lines in the OT spectrum corresponding to a redshift lower limit of $z = 1.619$.

In this letter we report on deep observations of the OT performed with the ESO VLT, NTT and 3.6 m telescopes. These observations allowed to extend the coverage of the OT light curve up to ∼10 days from the burst onset and to search for an underlying host galaxy.

## 2. Observations and results

The observations were performed with the 8 m VLT–Antu telescope equipped with the Focal Reducer/Low Dispersion Spectrograph (FORS1) on May 11 ($6.8'{\times}6.8'$ field of view and $0.2''$/pixel resolution), the ESO 3.5 m NTT equipped with the Superb Seeing Imager – 2 (SUSI2) between May 16–18 ($5.5'{\times}5.5'$ field of view and $0.16''$/pixel resolution), and the ESO 3.6 m telescope with the ESO Faint Object Spectrograph and Camera (EFOSC2) mounted at the F/8 Cassegrain Focus on May 20 ($5.5'{\times}5.5'$ field of view and $0.32''$/pixel resolution). We performed photometry in the Bessel–$R$ and Gunn–$I$ filters. The data were reduced using standard *ESO–MIDAS* and *IRAF* procedures for bias subtraction and flat–field correction. Photometry for each stellar object in the image was derived both with the DAOPHOT II and the ROMAFOT MIDAS–packages (Stetson 1987; Buonanno & Iannicola 1989). Point–like source $R$ magnitudes were derived by comparison with nearby stars, assuming $R = 16.5$ for the star at $\alpha = 13^{\rm h}38^{\rm m}00.82^{\rm s}$, $\delta = -80^\circ 29' 11.7''$ (Bloom et al. 1999), while the $I$ magnitudes were calibrated observing a number of Landolt photometric standards during the observational night (Landolt 1992). In Fig. 1 the field around the position of the OT as observed by the VLT–FORS1 (May 11; left panel) and NTT–SUSI2 (May 18; right panel) telescopes is

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* Partially based on data collected at the ESO VLT–FORS1 (Paranal), NTT–SUSI2 and ESO 3.6 m EFOSC2 (La Silla) telescopes

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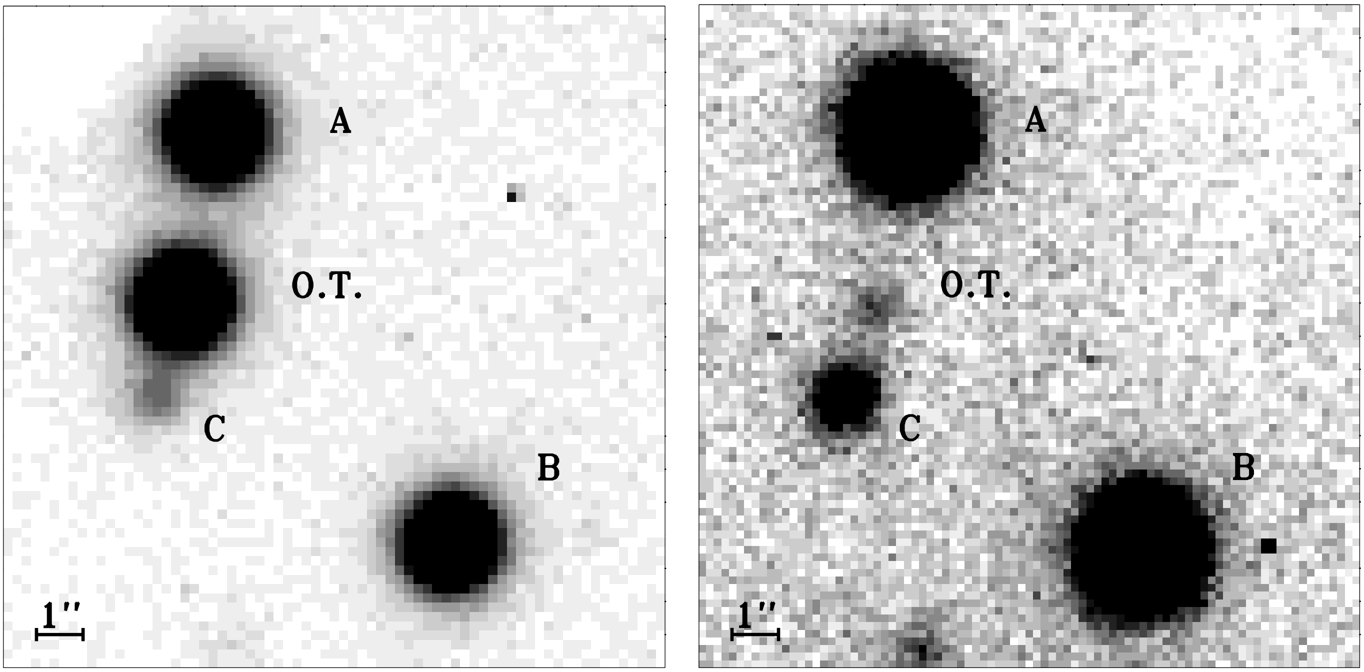


**Fig. 1.** The field of the GRB 990510 afterglow as seen by the VLT–FORS1 in the $R$ band when the OT was $R = 19.1$ (left panel; 600 s exposure time) and the NTT–SUSI2 in the $R$ band when the OT was $R = 23.7$ (right panel; 3000 s). The optical afterglow is marked (OT).

**Table 1.** VLT, NTT and ESO 3.6 m magnitudes of the afterglow.

| Date (1999 UT) | Telescope | Exposure (s) | Filter | Magnitude[a] | Seeing (″) | Reference |
|---|---|---|---|---|---|---|
| May 11.047 | Antu/VLT–FORS1 | 10 | $R$ | 18.96±0.02 | 1.2 | 1 |
| May 11.136 | Antu/VLT–FORS1 | 600 | $R$ | 19.10±0.02 | 1.2 | 2 |
| May 16.110 | ESONTT–SUSI2 | 1800 | $R$ | 23.0±0.1 | 1.8 | 3 |
| May 17.107 | ESONTT–SUSI2 | 2400 | $R$ | 23.4±0.1 | 1.2 | 4 |
| May 18.131 | ESONTT–SUSI2 | 3000 | $R$ | 23.7±0.1 | 1.1 | 4 |
| May 20.190 | ESO 3.6 m EFOSC2 | 900 | $I$ | >23.6 | 1.0 | – |

[a] Uncertainties are at 1$\sigma$ confidence level.
*References:* [1] Covino et al. 1999a; [2] Covino et al. 1999b; [3] Marconi et al. 1999a; [4] Marconi et al. 1999b.

shown. Table 1 reports the results of the photometry for each of the pointings.

The mediocre seeing of the observations is in part due to the low OT elevation at the Paranal and La Silla Observatories. The May 18 NTT–SUSI2 image is the deepest and the one obtained with the best seeing (1.1″). In this image the OT is sufficiently faint to allow for a sensitive search for additional underlying point–like or diffuse objects. Both the DAOPHOT II and the ROMAFOT packages failed to associate a point–like Point Spread Function (PSF) to the OT. Moreover the flag that records the sharpness of each single object is consistent with diffuse emission either from an object with broad–wings or from two point–like nearby objects. However the presence of the OT itself plays an important role in increasing the background level which, in turn, translates into a reduced detection sensitivity. An underlying point–like object (either an unresolved host galaxy or a faint star) could have been detected if its magnitude were smaller than $R \sim 26.6$ and with a angular extension $> 1''$. Note that the HST image of the GRB 990123 field showed a candidate host galaxy of $\sim 1''$ extension (Fruchter et al. 1999). If a similar size host were to be expected in our case (the redshift of the two bursts is similar), this would likely remain unresolved in our images.

We also can infer a lower limit for a host galaxy near but PSF–separated from the OT by summing the three NTT–SUSI2 images carried out on May 16/17/18: a 7200 s exposure image in the $R$–band was obtained and analysed. Stellar objects in the image were searched with the DAOPHOT II; the faintest point–like star that we detected have $R$~27 (S/N~5).

An alternative way of detecting a host galaxy consists in monitoring the low flux end of the afterglow decay: the presence of an unresolved galaxy causes the light curves to flatten when the flux of the OT becomes comparable to that of the host. This method was successfully applied to the afterglow light curves, obtained from days to months after the GRB event, in the cases of GRB 971214 (Odewahn et al. 1998), GRB 980703

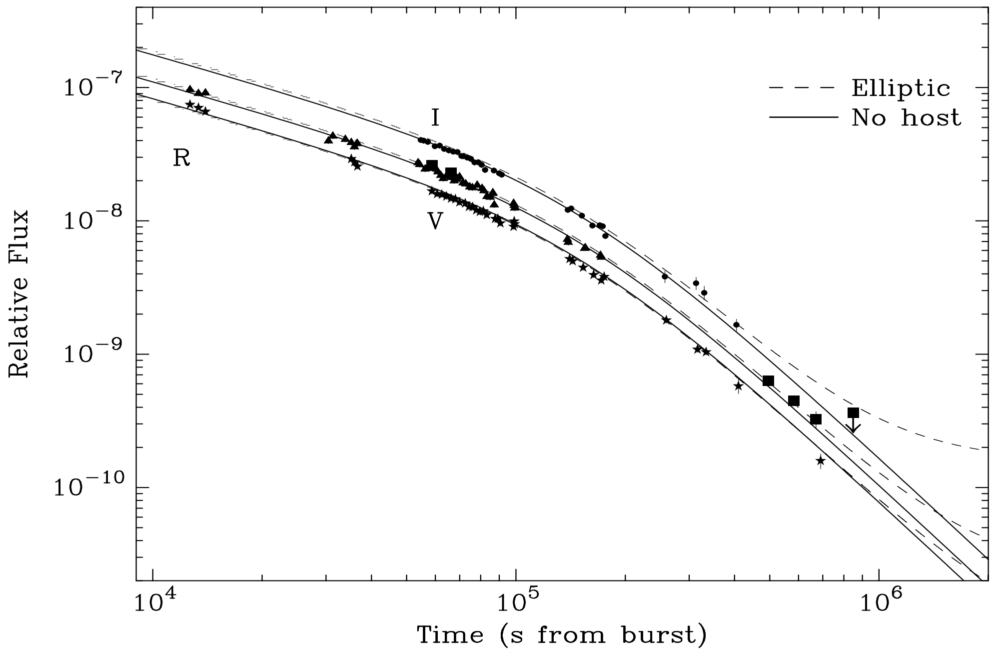


**Fig. 2.** GRB 990510 afterglow $V$, $R$ and $I$ band light curves fitted using Eq. 1 under two different hypothesis: (a) no underlying host galaxy (solid lines), and assuming a $R = 26.6$ (b) elliptical galaxy (dashed lines). The underlying galaxy is placed at $z = 1.6$ and stellar evolution was taken into account. Filled squares mark our dataset. See text for details.

(Bloom et al. 1998; Castro–Tirado et al. 1999) and GRB 970508 (Zharikov & Sokolov 1999). Typical values of the known underlying galaxies are in the $R$=22–27 range (Hogg & Fruchter 1999 and references therein).

We applied the same technique to GRB 990510. In order to further characterise the afterglow decay we collected all the published fluxes of the OT in the $V$, $R$ and $I$ bands (Axelrod et al. 1999; Galama et al. 1999; Harrison et al. 1999; Kaluzny et al. 1999a,b; Stanek 1999; Stanek et al. 1999a,b; Pietrzyński & Udalski 1999a,b,c; Beuermann et al. 1999). When available we used the known uncertainties, while in the remaining cases the 10% of the flux measurement was considered as a typical error value. We fitted the $V$, $R$ and $I$ light curves (36, 43 and 32 data points, respectively) by using the empirical model for the flux evolution, $F_\nu(t)$, described in Marconi et al. (1999a)

$$F_\nu(t) = \frac{k_\nu t^{-\alpha_1}}{1 + (t/t_*)^{\alpha_2 - \alpha_1}} \quad . \tag{1}$$

Stanek et al. (1999b; hereafter S99) adopted the same model. The eariler model proposed by Bloom et al. (1999; see also Harrison et al. 1999) is similar. $F_\nu(t)$ is characterised by four free parameters: two power–law indices $\alpha_1$ and $\alpha_2$ (for the earlier and the later time part of the decay, respectively), a folding time $t_*$ where the two power–laws match, and the normalisation $k_\nu$. Table 2 summarises the results obtained from the fitting. Note that parameter uncertainties are $1\sigma$ for a single interesting parameter; all parameters in the fit were left free to vary. Similar results were reported by S99. We ascribe their somewhat smaller uncertainties (and larger $\chi^2$) to the fact in evaluating the uncertainties in each parameters S99 held the other parameters fixed. We note that a different assumed values of the measurement uncertainties may affect the fit and account for the different $\chi^2$ values quoted in our work and in S99. Fig. 2 shows the $V$, $R$ and $I$ relative flux light curves (obtained from $M_{V,R,I}$=–2.5 log $F_{V,R,I}$) fitted with the model in Eq. 1 keeping fixed $\alpha_1$, $\alpha_2$ and $t_*$ to the best values obtained for the $R$ band and leaving free to vary only the normalisation (solid lines). A $\chi^2$ of 95 for 105 degree of freedom ($dof$) corresponding to a $\chi^2/dof$ of 0.9 was obtained. Note that in this case, given the larger number of data points in the $R$ filter, the simultaneous fit in the $V$, $R$ and $I$ bands is biased towards the $R$–band light curve. The derived fitting parameters are nearly filter–independent, within the statistical uncertainties, suggesting a similar temporal evolution of the emission in the $VRI$ bands where only the normalisation $k_\nu$ varies; this was already noted by Bloom et al. (1999) and Marconi et al. (1999a).

**Table 2.** GRB 990510 light curve fit.

| Band | $\alpha_1$ | $\alpha_2$ | $t_*$ (days) | $\chi^2/dof$ [a] |
|---|---|---|---|---|
| $R$ | $0.75 \pm 0.03$ | $2.46 \pm 0.06$ | $1.3 \pm 0.1$ | 1.1 |
| $V$ | $0.88 \pm 0.03$ | $2.68 \pm 0.13$ | $1.8 \pm 0.2$ | 0.8 |
| $I$ | $0.77 \pm 0.05$ | $2.34 \pm 0.11$ | $1.6 \pm 0.2$ | 0.8 |

[a] $dof$ stands for degree of freedom.
*Note:* Uncertainties refer to 1 $\sigma$ confidence level.

To include the possibility of an underlying galaxy we added to the model described in Eq. 1 a fifth free parameter (i.e. a constant) corresponding to the host galaxy flux. Galaxy color indices strongly depend on the morphology and distance of the host and were adopted from Buzzoni (1995, 1999 and references therein) which take into account the effects of stellar evolution within the galaxy. We consider a set of color index values corresponding to $z = 1.6$ and to three different morphologies: elliptical ($V$–$R$=2.4; $R$–$I$=2.1), spiral (Sb; $V$–$R$=0.32; $R$–$I$=1.02) and irregular ($V$–$R$=0.15; $R$–$I$=0.55). Moreover we corrected the set of data for absorption in the direction of GRB 990510

($E_{B-V}$ ≃0.20; Stanek et al. 1999b) which corresponds to an $E_{V-R} \simeq E_{R-I} \simeq$ 0.15.

Dashed lines in Fig. 2 show the fit obtained by using the colors of an elliptical host galaxy of magnitude $R = 26.6$. We first fitted the light curves as before without the deepest points (one in the $V$, three in the $R$ and one in the $I$ band), then we added the deep data of this paper, keeping fixed $\alpha_1$, $\alpha_2$ and $t_*$, and leaving the normalisation and the host galaxy flux parameters free to vary. In all cases we obtained a $\chi^2/dof$ in the 0.9–1.1 range. As expected, the unchanged value of the reduced $\chi^2$ testifies that the constant parameter does not significantly improve the fit. In the case of an elliptical host the lower limit on the galaxy magnitude is strongly driven by the OT upper limit in the $I$–band; any (elliptical) object brighter than $R = 26.6$ would produce a levelling off of the OT $I$–band light curve that is not observed. The spiral and irregular host galaxy cases are consistent with the $I$–band data, while the lower limit is driven by the VLT deep observation in the $V$–band (Beuermann et al. 1999); any object brighter than $R = 26.6$ must be brighter than observed in the $V$ band. If the host galaxy is farther than $z = 1.6$, lower magnitudes are to be expected, while color indeces (which are differential quantities) remain nearly constant (at least up to $z \simeq 2.0$).

## 3. Conclusions

We reported on the deep optical observations of the GRB 990510 OT. We are able to follow the OT in the $R$ band down to 23.7 and derive an upper limit in the $I$ band ($> 23.6$). We propose a functional form for the fitting of the multi-band optical light curve (see also S99; Bloom et al. 1999) and derive strong upper limits on the magnitude of galaxy hosting the GRB. In particular, our photometric data exclude an elliptical host galaxy brighter than $R$=26.6. Further observations are needed in order to look for a faint R≥27 galaxy host.

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