

# ***BVR<sub>c</sub>I<sub>c</sub>* light curves of GRB970508 optical remnant and colors of underlying host galaxy**

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**Abstract.** Optical observations of the GRB970508 optical remnant were continued with the 6-m telescope of SAO RAS in standard the *BVR<sub>c</sub>I<sub>c</sub>* bands in Oct.-Dec. 1997 and in Jan. 1998. The results of photometry of the GRB970508 remnant and of three nearby galaxies are presented. The *BVR<sub>c</sub>I<sub>c</sub>* light curves of the GRB970508 remnant can be described by a power law plus a constant  $F(t) = F_0(t - t_0)^\alpha + C$ . In determination of parameters of the faint host galaxy we used the results of our *BVR<sub>c</sub>I<sub>c</sub>* photometry of May-August, 1997, the data of recent observations with Keck-II and WHT telescopes and also the data of photometry of *R<sub>c</sub>* and *B* bands obtained by other authors based on our secondary standards. The level-off from the initial power law decline seen in the first months after the burst was observed in all bands. The effect is the strongest in the *I<sub>c</sub>* band: the difference on the last date of the *I<sub>c</sub>* observations reaches  $\sim 1.3$  mags. The best  $\chi^2$ -fits for  $F_0$ ,  $\alpha$ ,  $C$  parameters of the data in each of 4 bands point to the presence of a constant faint source with  $I_c = 24.13 \pm 0.28$ ,  $R_c = 25.55 \pm 0.19$ ,  $V = 25.80 \pm 0.14$ ,  $B = 26.68 \pm 0.14$ . The average  $\alpha$  is  $-1.23 \pm 0.04$ . The optical remnant has a power law spectrum with a spectral slope equal to  $-1.10 \pm 0.08$  and does not change after the optical curve maximum. The *BVR<sub>c</sub>I<sub>c</sub>* spectrum together with the absolute magnitude of the constant component  $M_{B_{rest}} = -17.5 \pm 0.3$ , and the linear size of the underlying host galaxy  $d \sim 3$  kpc conform to a host galaxy, such as a starburst dwarf, a red starburst dwarf, an irregular dwarf, a HII galaxy, or a blue compact dwarf galaxy. All these types of dwarf galaxies show evidence of starburst or post starburst activity. The galaxy G2 has a spectrum similar to that of the host GRB galaxy and lies at the projected distance of  $\sim 20$  kpc from GRB.

**Key words:** gamma-rays: bursts – galaxies: dwarf

## **1. Introduction**

After the launch of the BeppoSAX satellite (Boella et al., 1997) a new era began in the search and optical investigation of gamma-ray bursts. The precise locations determined with the Wide Field Cameras on board the BeppoSAX satellite

allowed one to discover X-ray (Costa et al., 1997) and radio (Frail et al., 1997) afterglow of gamma-ray bursts. The discovery of optical transients accompanying the gamma-ray bursts was first announced by Groot et al., 1997. During a year after the discovery of GRB970228, optical counterparts were reliably detected for 4 other gamma-ray bursts: GRB970508 (Bond, 1997, GRB971224 (Halpern et al., 1997), GRB980326 (Groot et al., 1998), GRB980329 (Djorgovski et al., 1998). The study of optical afterglow light curves and of the properties of underlying optical GRB counterparts gives a chance to understand the physics of the GRB phenomenon.

This article presents the results of optical follow-up observations of the variable source associated with the GRB970508 remnant. The first results of our multi-color photometry from May to Aug. 1997 of the GRB970508 optical remnant were reported by Sokolov et al., 1998. In this paper we report the results of a further *BVR<sub>c</sub>I<sub>c</sub>* photometry performed until up to Jan. 1998. The next section is dedicated to the results of CCD photometry of the optical remnant in different filters and to an interpretation of the optical light curves with power-law  $\chi^2$  fits. The photometry of nearby galaxies to the GRB970508 optical remnant is given. Discussion and summary constitute Sect. 3.

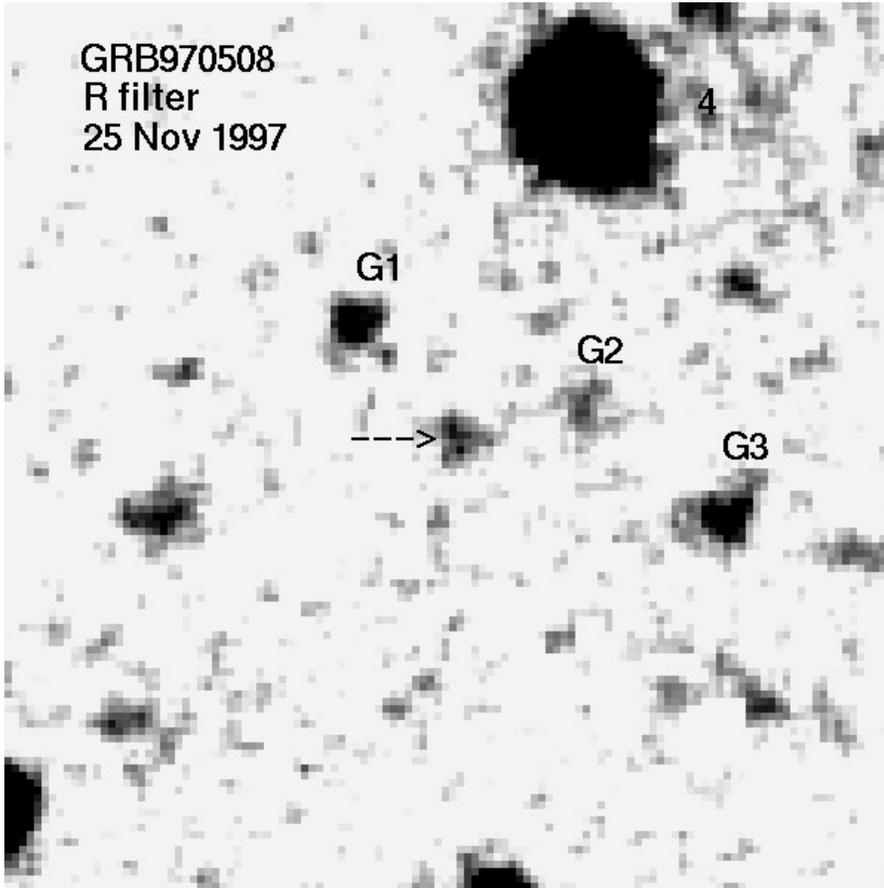
## **2. The field of GRB970508 optical counterpart**

Observations of the GRB970508 optical remnant were performed using the primary focus CCD photometer of the 6m telescope SAO RAS (see Sokolov et al., 1998). The observations were carried out with the standard (Johnson - Kron - Cousins) photometric *BVR<sub>c</sub>I<sub>c</sub>* system. Here we present the results of our observations in the period Oct. 1997 - Jan. 1998. The magnitudes in the *BVR<sub>c</sub>I<sub>c</sub>* bands with associated errors for the GRB970508 optical counterpart are given in Table 1. Our last *B* point (denoted by \* in Table 1) was obtained by A. Kopylov. Fig. 1 shows a part of the deep *R<sub>c</sub>* band image of GRB970508 field. An arrow points the GRB970508 optical remnant and nearby galaxies. These galaxies are denoted as G1, G2 and G3 in Fig. 1.

The magnitudes and colors of the galaxies G1, G2, G3 are given in Table 2. The photometry of those objects was obtained using a digital sum of all images of the GRB970508 field with a seeing better than  $1.8''$ . We made a photometric calibration using our secondary photometric standards from Sokolov et al., 1998.

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**Fig. 1.** The  $R_c$  band field near GRB 970508 optical source. The image size is  $33'' \times 33''$ . N-top, E-right. The G1, G2, G3 are nearby galaxies. The arrow denotes an optical remnant of GRB970508.

**Table 1.** The SAO RAS photometry of OT GRB970508 in Oct. 1997 - Jan. 1998.

UT	$t - t_0$	$B$	$V$	$R_c$	$I_c$
09.000 Oct.	154.12			$24.30 \pm 0.2$	
09.000 Nov.	185.12		$25.10 \pm 0.17$	$24.7 \pm 0.15$	
25.00	201.09		$25.50 \pm 0.35$		$23.90 \pm 0.14$
25.00	201.16			$24.7 \pm 0.14$	
01.00 Dec*.	206.01	$25.75 \pm 0.30$			
24.87 Jan.	260.96			$24.96 \pm 0.17$	
24.87	260.96		$25.44 \pm 0.25$		

**Table 2.** Magnitudes and colors of GRB970508 field objects without galaxy extinction correction.

Object	$B$	$V$	$R_c$	$I_c$	$B - V$	$V - R_c$	$R_c - I_c$
G1	$25.22 \pm 0.12$	$24.61 \pm 0.07$	$24.23 \pm 0.05$	$24.21 \pm 0.16$	$0.61 \pm 0.14$	$0.38 \pm 0.09$	$0.02 \pm 0.17$
G2	$> 26.7$	$26.1 \pm 0.25$	$25.31 \pm 0.12$	$23.73 \pm 0.08$	$> 0.6$	$0.79 \pm 0.25$	$1.58 \pm 0.14$
G3	$25.29 \pm 0.13$	$24.79 \pm 0.08$	$24.20 \pm 0.04$	$23.99 \pm 0.09$	$0.50 \pm 0.15$	$0.59 \pm 0.09$	$0.20 \pm 0.10$

The total exposure times for each filter were  $B$  4800 sec.,  $V$  14200 sec.,  $R_c$  13950 sec.,  $I_c$  10800 sec.. The galaxies G1, G3 are blue galaxies with close magnitudes and similar spectra which probably attests that they have the same  $z$ . The galaxy G2 is red with  $R_c - I_c = 1.58 \pm 0.14$ .

The magnitudes of  $g = 24.5 \pm 0.4$  and  $r = 24.8 \pm 0.4$  for G1 from Djorgovski et al., 1997 agree with our  $V$  and  $R_c$  magnitudes with subsequent offset between broadband magnitudes in the Gunn photometric system and the Johnson-Kron-

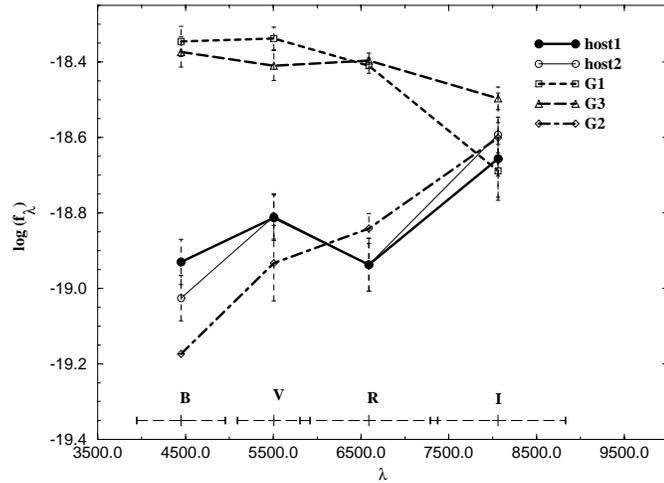
Cousins photometric system  $V = g + 0.031$  and  $R_c = r - 0.343$  (see. Frei and Gunn, 1994) and  $\approx 0.6$  brighter than the STIS/ $R$  magnitude ( $R = 24.8 \pm 0.2$ ) from Pian et al., 1997. The difference may be related to the  $R$  magnitude interpolated by Pian et al., 1997 for G1. This interpolation is done by a power-law spectrum consistent with the  $(V - H)$  color index. For the G2 galaxy our  $R_c = 25.31 \pm 0.12$  magnitude agrees with the Pian et al., 1997 ( $25.5 \pm 0.2$ ) magnitude.

**Table 3.** The  $\chi^2$  fits for  $BVR_cI_c$  lights curves of GRB 970508 remnant ("host1" case).

Filter	$\chi^2/(d.o.f.)$	$F_0(\text{mag})$	$\alpha$	F (mag)	$\log(F(\frac{\text{erg}}{\text{cm}^2\text{s}\text{\AA}}))$
B	15.2/13	$19.617 \pm 0.15$	$-1.28 \pm 0.04$	$26.68 \pm 0.14$	$-18.88 \pm 0.06$
V	35.1/13	$19.236 \pm 0.14$	$-1.22 \pm 0.04$	$25.80 \pm 0.14$	$-18.76 \pm 0.08$
$R_c$	164/37	$18.779 \pm 0.11$	$-1.23 \pm 0.02$	$25.55 \pm 0.19$	$-18.89 \pm 0.07$
$I_c$	43.9/11	$18.330 \pm 0.27$	$-1.18 \pm 0.07$	$24.13 \pm 0.28$	$-18.61 \pm 0.11$

**Table 4.** The  $\chi^2$  fits for  $BVR_cI_c$  light curves of GRB 970508 remnant with  $\alpha = -1.23$  ("host2" case).

Filter	$\chi^2/(d.o.f.)$	$F_0$ (mag)	F (mag)	$\log(F(\frac{\text{erg}}{\text{cm}^2\text{s}\text{\AA}}))$
B	17.9/14	$19.668 \pm 0.15$	$26.92 \pm 0.14$	$-18.98 \pm 0.08$
V	34.7/14	$19.232 \pm 0.14$	$25.79 \pm 0.14$	$-18.76 \pm 0.08$
$R_c$	164/38	$18.779 \pm 0.11$	$25.55 \pm 0.19$	$-18.89 \pm 0.07$
$I_c$	44.9/12	$18.289 \pm 0.27$	$23.97 \pm 0.28$	$-18.54 \pm 0.11$

**Fig. 2.** Observational  $BVR_cI_c$  spectra of GRB970508 remnant field objects (G1, G2 and G3) corresponding to Fig. 1 are shown. Two variants of broad-band spectra of the GRB host galaxy denoted as "host1" and "host2" (see the text) are also shown. The X axis is  $\lambda(\text{\AA})$ , the Y axis is  $\log(f_\lambda)$ . The  $f_\lambda$  is given in  $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ . The FWHTs for the  $BVR_cI_c$  bands are shown under the figures.

Observational broad-band spectra of nearby galaxies are shown in Fig. 2.

### 3. The GRB970508 $BVR_cI_c$ light curves

In Figs. 4,5,6,7 we present the  $BVR_cI_c$ -band light curves of the optical remnant of GRB970508. We included here the results of our photometry of May 1997- Jan 1998 (labeled by  $\blacksquare$ ), the data of recent observations with the Keck-II (Bloom et al., 1998  $\diamond$ ) and the WHT telescopes (Castro-Tirado et al., 1998  $\triangle$ ) and the data of  $R_c$  and B band photometry obtained by other authors based on our secondary standards (Pedersen et al., 1998 square; Garcia et al., 1997,  $\bullet$ ; Galama et al., 1998, 1998,  $\circ$ ). Also we have included two points from Mignoli et al., 1997 ( $*$ ) and Metzger et al., 1997 ( $\nabla$ ).

#### 3.1. The "host1" case

We fitted the data by a power law plus a constant  $F(t) = F_0 t^\alpha + C$  in all bands using the  $\chi^2$  fit (denoted as "host1"). The  $F_0$ ,  $\alpha$  and  $C$  are fit parameters independent for every band. Our fit results are presented in Table 3. We switched from stellar magnitudes of the Cousins system to absolute fluxes in  $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$  with the data on  $\alpha\text{Lyr}$  published by Fukugita et al., 1995.

Magnitude errors were calculated with the uncertainty of the fit  $\sigma_{\text{mag}}^2 = \sigma_{\chi^2}^2 / \sqrt{N_{\text{point}}}$ .

For a host object we found:  $B = 26.68 \pm 0.14$ ,  $V = 25.80 \pm 0.14$ ,  $R_c = 25.55 \pm 0.19$ ,  $I_c = 24.13 \pm 0.28$ . Taking into account the galactic absorption  $E(B - V) = 0.03$  for color indexes we have:

$$(B - V) = 0.88 \pm 0.20; (B - V)_0 = 0.85 \pm 0.20$$

$$(V - R_c) = 0.25 \pm 0.24; (V - R_c)_0 = 0.23 \pm 0.24$$

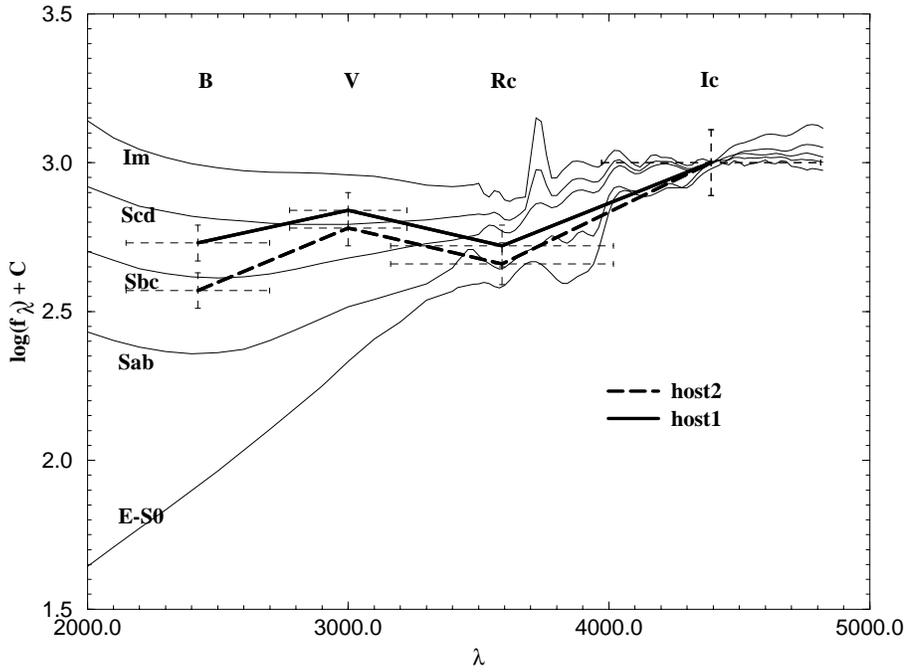
$$(R_c - I_c) = 1.42 \pm 0.34; (R_c - I_c)_0 = 1.40 \pm 0.34$$

The optical fluxes for the GRB970508 remnant in 300 day after the gamma-ray burst is  $\sim 19\%$  in B,  $\sim 24\%$  in V,  $\sim 23\%$  in  $R_c$ ,  $\sim 25\%$  in  $I_c$  relative to the host object fluxes in the B, V,  $R_c$ ,  $I_c$  bands respectively. The decay slope  $\alpha$  (for the decay phase) of optical brightness of the GRB970508 remnant is constant,  $\langle \alpha \rangle = -1.23 \pm 0.04$ , within the errors for the 4 bands (see Table 3). It follows that the optical remnant spectrum does not change after the optical light curve maximum and the GRB970508 optical afterglow has a power law spectrum with a spectral slope equal to  $-1.10 \pm 0.08$  (Sokolov et al., 1998, Metzger et al., 1997a).

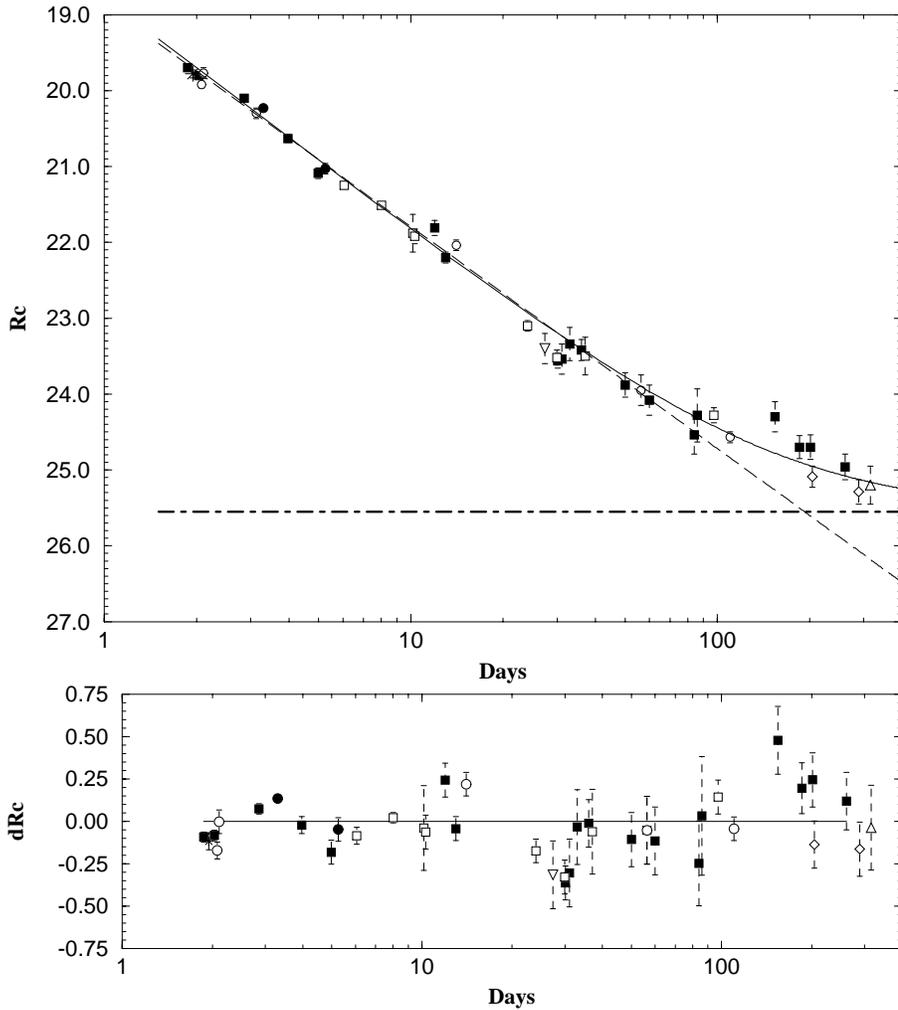
#### 3.2. The "host2" case

We also fitted our data by a power law plus a constant  $F(t) = F_0 t^\alpha + C$  with  $\alpha = -1.23$  (denoted as "host2"). We present results of this fit in Table 4. Colors for a constant object from the last fit are

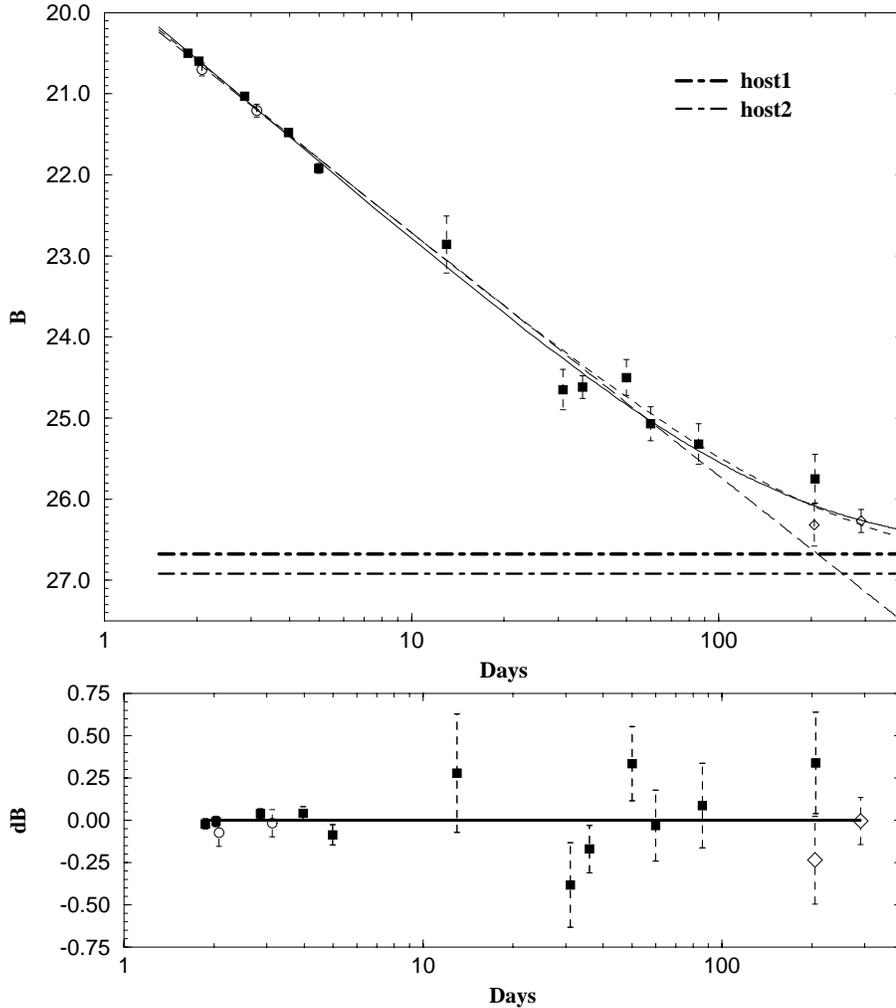
$$(B - V) = 1.12 \pm 0.20; (B - V)_0 = 1.10 \pm 0.20$$



**Fig. 3.** The  $BVR_cI_c$  broad-band spectrum  $\log(f_\lambda) + Constant$  for the host object (with "host1" and "host2" fits) for  $z = 0.835$  is shown. The observing bands have been shifted to the rest frame of GRB970508. The spectral energy distribution for different morphological types of galaxies, E-S0, Sab, Sbc, Scd, Im, from Pence (1976) are shown for comparison.



**Fig. 4.** The  $R_c$  light curve of the GRB970508 optical remnant. The power law fit to the May-Aug. 1997 from Sokolov et al., 1998 is represented by the long-dashed lines. Indicated by the solid line is a fit by the whole data of a power law plus a constant with the parameters from Table 3. The dot-dashed lines correspond to constant object magnitudes for "host1, host2" cases. The lower panel: the fit to the power law decay plus a constant ("host1") subtracted from the observational data. The symbols correspond to Sokolov et al. (1998, black square), Galama et al., (1998,  $\circ$ ), Garsia et al., (1998;  $\bullet$ ), Mignole et al., (1997) (\*), Metsger et al., (1997;  $\nabla$ ), Pedersen et al., (1998, square), Bloom et al., (1998,  $\diamond$ ), Castro-Tirado et al., (1998,  $\triangle$ ).



**Fig. 5.** The  $B$  light curve of the GRB970508 optical remnant. The power law fit to the May-Aug. 1997 from Sokolov et al., 1998 is represented by the long-dashed lines. Indicated by the solid line is a fit by the whole data of a power law plus a constant with parameters from Table 3. The power law fit with  $\alpha = -1.23$  is given by the dashed line. Dot-dashed lines correspond to constant object magnitudes for "host1" and "host2" case. The lower panel: the fit to the power law fading plus a constant ("host1") subtracted from the observational data. The symbols correspond to Sokolov et al. (1998, black square), Galama et al., (1998,  $\circ$ ), Bloom et al., (1998,  $\diamond$ ).

$$(V - R_c) = 0.26 \pm 0.24; (V - R_c)_0 = 0.24 \pm 0.24$$

$$(R_c - I_c) = 1.47 \pm 0.34; (R_c - I_c)_0 = 1.45 \pm 0.34,$$

without and with  $E(B - V) = 0.03$  correspondingly.

The spectra of the optical transient obtained with the Keck-II 10-m telescope on 11 May near the brightness maximum demonstrated several absorption features which were interpreted as MgII and Fe II with  $z = 0.835$  and Mg II with  $z = 0.767$  (Metzger et al., 1997). The  $BVR_cI_c$  broad-band spectra for the "host1" and "host2" cases in the rest frame of the host object for  $z = 0.835$  are displayed in Fig. 3. The spectral energy distribution for galaxies with different morphological types, E-S0, Sab, Sbc, Scd, Im, from Pence, 1976 are shown for comparison.

The host object color  $R_c - I_c$  corresponds to E-Sab galaxy types. The color indexes  $B - V$  and  $V - R$  show flat spectrum which conforms with Sbc-Im galaxies.

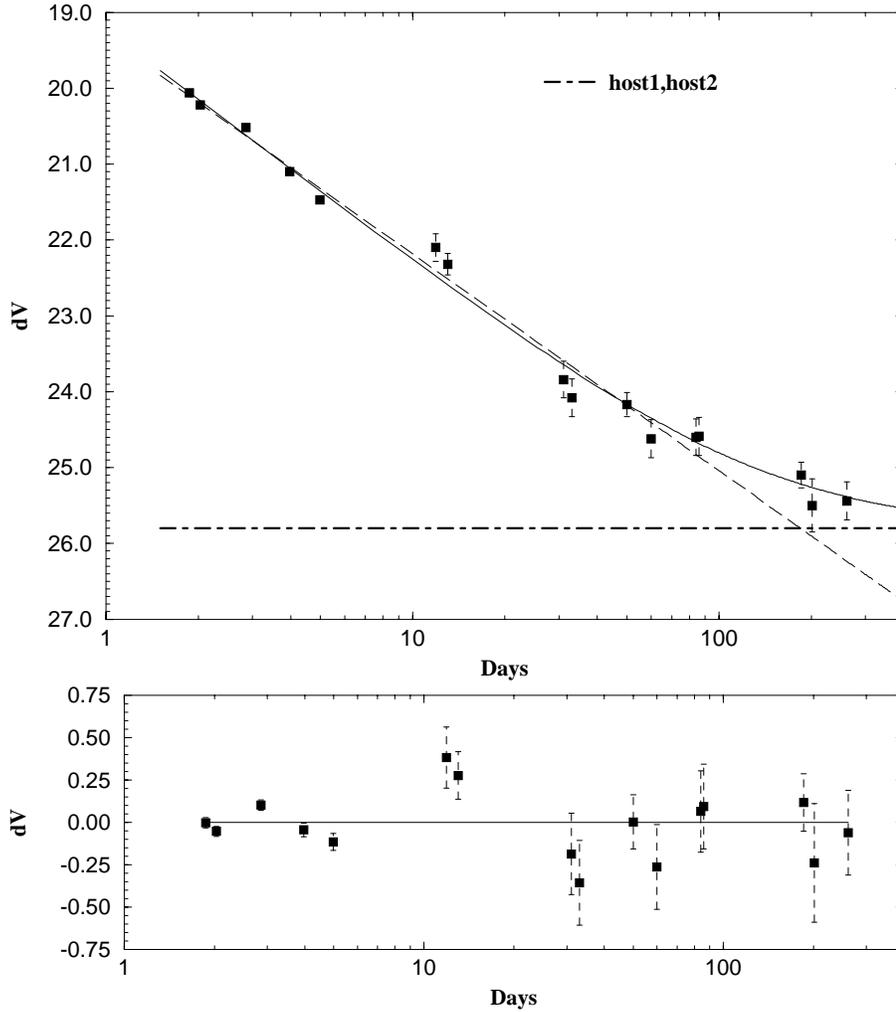
#### 4. Discussion

The light curves of the GRB970508 optical remnant show deviation from single power law decay for the optical transient. On the average the brightness fading in all filters can be described

by a power law with an additional constant source. However we note that the introduction of a constant to the power law fit did not improve the  $\chi^2$  substantially. From too large  $\chi^2$  we conclude that a single power law plus a constant is not a good description of all observational data. A single power law describes the light curve on the average on a large-time scale of brightness decay. But besides the exponential law of the source brightness fading on first days after the maximum (Sokolov et al., 1998) a further intrinsic variability of the fading is possible too.

Observations in four optical bands during all brightness fading period of the GRB970508 optical counterpart allowed us to make the following conclusions on the character of optical behavior of the GRB970508 remnant and the properties of its host galaxy.

1) In the  $I_c$  band the decay slows down from the 31th day onwards. We conclude that the evidence for flattening of the light curve at late times is convincing. The brightness of the GRB optical remnant was  $\sim 25\%$  from the host galaxy brightness in 300th day from the gamma-ray burst. We note here that HST/NICMOS flux measurements (Pian et al., 1997) in the  $H$  band gave  $6.2 \pm 1.5 \mu\text{Jy}$ , but not  $3 \pm 1 \mu\text{Jy}$  as was expected for the power-law brightness fading in the ground-based  $I$  and  $K$  bands. It was necessary to extrapolate these data to the  $H$  band, as-



**Fig. 6.** The  $V$  light curve of the GRB970508 optical remnant, the Lines and symbols are the same as in Fig. 4.

suming the same power-law spectrum slope which had been observed at the brightness maximum phase (Metzger et al., 1997a; Sokolov et al., 1998).

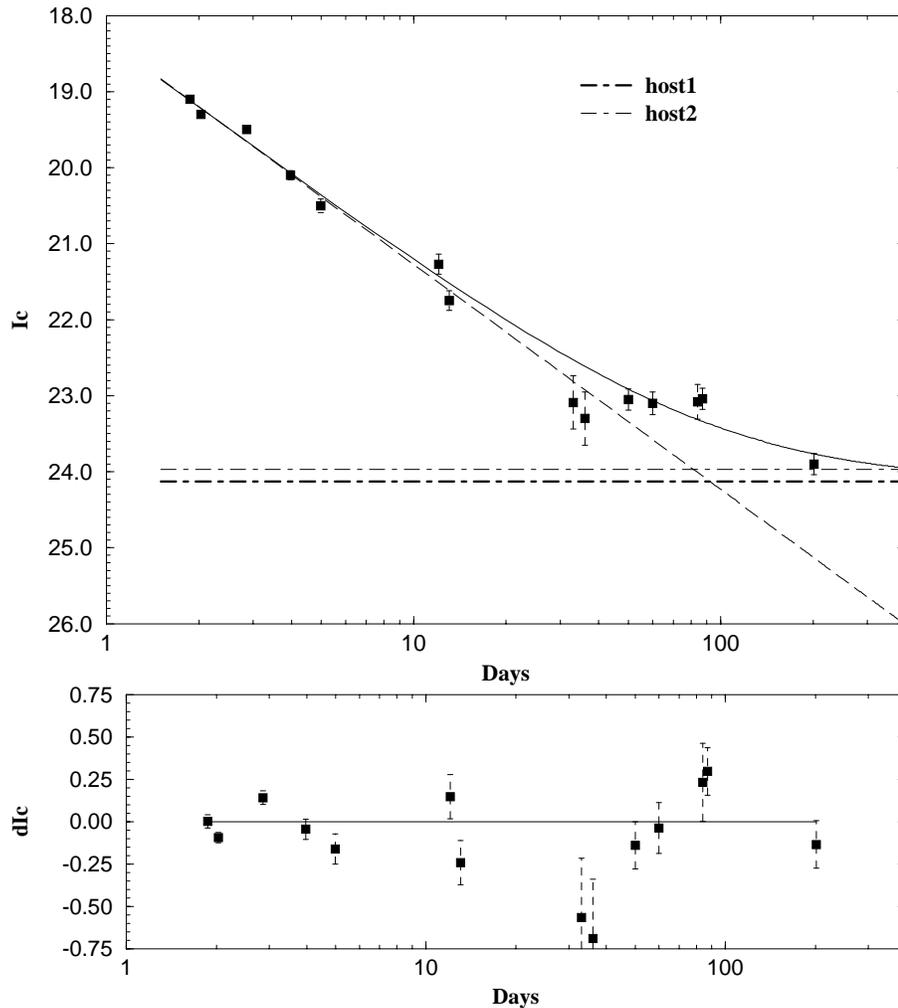
2) The temporal slope  $\alpha$  of the decay phase of optical brightness of the GRB970508 remnant is constant,  $\langle \alpha \rangle = -1.23 \pm 0.04$ , within the errors over all 4 bands. It follows that the optical remnant spectrum does not change after the optical light curve maximum and the GRB970508 optical afterglow has the power law spectrum with the spectral slope equal to  $-1.10 \pm 0.08$ .

3) The  $R_c = 25.55 \pm 0.19$  magnitude for the possible underlying galaxy is consistent with the limits derived by Pian et al., 1997 ( $R_c > 25.5$ ) and the host object  $R$  magnitude is consistent from Pedersen et al., 1998 ( $R_c = 25.5 \pm 0.4$ ). The results of our power law fits with the additional constant source is in good agreement with the late observations in the  $B$  and the  $R_c$  bands with the Keck-II (Bloom et al., 1998) and the WHT (Castro-Tirado et al., 1998).

4) If the observed  $BVR_cI_c$  spectrum belongs to the host galaxy of GRB, then we can calculate some physical parameters of the galaxy and its possible type. For Friedmann model with  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $q_0 = 0.5$ , and, assuming the

redshift of the host galaxy  $z = 0.835$ , we obtain an absolute magnitude  $M_{B_{rest}} = -17.5 \pm 0.3$  in the rest frame of the host galaxy. It should be noted that the effective wavelength of the  $R_c I_c$  bands just corresponds to the rest frame  $U_{rest}$  and  $B_{rest}$ . This allows us to calculate the K-correction, which is  $+1.3 \pm 0.3$  and the color  $(U - B)_{rest} = +0.3 \pm 0.3$ . We estimate the linear size of the host galaxy according to the HST/STIS observations (Pian et al. 1998). If it is  $R_c = 25.55$ , then the upper limit of the size of a possible extended source may be a few tenths of an arcsecond. From the HST/NICMOS observations an additional limit ( $0''.4$ ) is obtained for underlying extended component. With the understanding that the true size may be slightly larger or smaller, we use for the effective linear size the value of  $\sim 3$  kpc. Taking into account the spectrum in Fig. 3, we conclude that the host galaxy may be either a starburst dwarf, or a red starburst dwarf, or an irregular dwarf HII galaxy, or a blue compact dwarf galaxy. All these types of dwarf galaxies show evidence of starburst or post starburst activity.

5) The nearest faint galaxy G2 has a similar spectrum and lies at a projection distance of about 20 kpc from the GRB host galaxy and is possibly a member of a compact group of galaxies. It is also possible that there is a galaxy on the line of



**Fig. 7.** The  $I_c$  light curve of the GRB970508 optical remnant. The lines and symbols are the same as in Fig. 4.

sight, which has  $z = 0.767$  (Metzger et al., 1997) and may have an additional effect on the spectrum (Natarajan et al., 1997).

However it is possible that the  $BVR_cI_c$  spectrum within the errors can be fitted by a single power law  $F_\nu \sim \nu^{-\beta}$  with  $\beta \approx 3$ .

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## References

- Bloom J., S. R. Kulkarni, S. G. Djorgovski., D. A. Frail, 1998, GNC Circular #30.
- Boella G., Butler R.C., et al., 1997, A&AS, 122, 299
- Bond H.E., 1997, IAU Circ No.6654
- Castro-Tirado A.J., Gorosabel J., Galama T., Groot P., van Paradijs., Kouveliotpo C., 1998, IAU Circ No.6848
- Costa E., Frontera F., Heise J., et al., 1997, Nature, 387, 783
- Djorgovski S. G., Metzger M. R., Kulkarni S. R., et al., 1997, Nature, 387, 876
- Djorgovski S. G., Kulkarni S. R., Sievers J., Frail D. & Taylor G., 1998, GNC Circular #40.
- Galama T., Groot P.J., van Paradijs J., et al., 1998, ApJ, 497, L13
- Garcia M. R., P.J. Callanan, D. Moraru et al., submitted to ApJ Lett., 1997; astro-ph/9710346
- Groot P. J., T. J. Galama., J. van Paradijs et al., 1997, IAU Circ No.6584
- Groot P.J., Vreeswijk P. M., Galama T.J., et al., 1998, GNC Circular #30.
- Halpern J., Thorstensen J., Helfand D., Costa E., & BeppoSAX team, 1997, IAUC 6788
- Metzger M. R., J. G. Cohen., F. H. Chaffee, R. D. Blandford., 1997, IAU Circ No.6676
- Metzger M. R., Djorgovski S.G., Kulkarni S. R., et al., 1997a, Nature, 387, 879
- Mignoli M., C. Bartolini, A. Bragaglia, et al., 1997, IAU Circ No.6661
- Natarajan P., Bloom J.S., Sigurdsson S., et al., 1997, New Astronomy, 2, 471
- Frail D. A., Kulkarni S. R., Nicastro L., Feroci M., Taylor G.B., 1997, Nature, 389, 261
- Frei Z. and Gunn J. E., 1994, AJ., 108, 1476
- Fukugita M., Shimasaku K., T Ichikawa., 1995, PASP., 107, 945
- Pedersen H., Jaunsen A.O., Grav T., et al., 1998, ApJ., 496, 311
- Pence W., 1976, ApJ., 203, 39
- Pian E. Fruchter A.S., Bergeron L.E. et al., 1997, ApJ., 492, L103
- Sokolov V.V., Kopylov A.I., Zharikov S.V., Feroci M., Nicastro L., Palazzi E., 1998, A&A., 334, 117