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ASTRONOMY AND ASTROPHYSICS

BVR_cI_c photometry of GRB 970508 optical remnant: May-August, 1997

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Abstract. We present the results of photometric observations of the variable optical source associated to the remnant of the gamma-ray burst GRB 970508 performed at the Special Astrophysical Observatory of the Russian Academy of Science (SAO RAS) from May to August 1997. The observations were carried out with the standard (Johnson-Kron-Cousins) photometric BVR_cI_c system using the 1-meter and 6-meter telescopes. The brightness of the optical source increased from $R_c = 21.19 \pm 0.25$ (May 9.75 UT) to $R_c = 19.70 \pm 0.03$ (May 10.77 UT), whereupon it was decaying in all the four BVR_cI_c bands during about one month after the burst. Between the 3rd and the 6th night after the GRB 970508 event, the flux decrease of the optical source follows an exponential law in all the four bands. In that period the broad-band spectrum of the object does not change and can be approximately described by the power law $F_\nu \propto \nu^{-1.1}$. The subsequent observations in BVR_cI_c bands have shown a reduction of the source brightness decrease rate. The source flux decay after the maximum in the R_c band is well described by a single power-law $F \propto t^{-1.171(\pm 0.012)}$ for the whole set of observations during 86 days. In the other bands the decay seems to slow down from the 31th day onwards. In particular, in the I_c band the source magnitude is about 23.1 from the 36th day after the GRB to the end of the observations (August 4, 1997).

Key words: gamma-rays: bursts

1. Introduction

Since their discovery in 1969 (Klebesadel et al. 1973) the gamma-ray bursts (GRBs) phenomenon is the subject of intensive observational and theoretical studies. The basic problem before 1997 was the lack of reliable counterparts to the sources of GRB (in quiet or transient state) in wave bands other than gamma-rays and, as a consequence, the total uncertainty of their distance. The situation changed after the Gamma-Ray Burst of February 28, 1997, GRB 970228 (Costa et al. 1997a) detected by the Italian-Dutch satellite BeppoSAX (Boella et al. 1997). Thank to the fast and accurate positioning of GRBs (a few arcminutes) obtainable through the combined capabilities of the Gamma-Ray Burst Monitor (GRBM) and Wide Field Cameras (WFCs) onboard this satellite, an X-ray and optical afterglow were observed for the very first time (Costa et al. 1997b, van Paradijs et al., 1997).

However, as was found out later, the optical data on the first GRB afterglow in the history were obtained with different instruments and in different photometric conditions and refer to different photometric systems and bands. The source brightness in different filters was determined at different times and besides, only a few reliable brightness determinations (not upper limits) have been gained while the object was bright enough. In the end, it led to the uncertainty in the interpretation of optical observations (see for example Sahu et al. 1997, Galama et al. 1997 and the Proceedings of the 4^{th} Huntsville GRB Symposium). But at least, one thing became clear after GRB 970228: the optical source – a gamma-ray burst remnant (GRBR) – can be observed during rather a long period, from one to several days, in sufficiently bright phase, with the brightness of $V < 23$.

By the end 1997, the optical afterglow of GRBs was reliably detected in 3 cases: GRB 970228, GRB 970508, GRB 971214. While the first and third optical transient sources (OTs) were not observed at SAO RAS close to their maximum brightness, for the second OT, related to GRB 970508 reported by the BeppoSAX team (Costa et al. 1997b; Piro et al. 1998) essential optical data helping to elucidate common observational signs of optical GRBRs have been obtained at SAO with the 1-m and 6-m telescopes. The second GRB with an optical afterglow was in a very favorable place in the northern sky (in the Camelopardalis constellation). The high declination of $\sim +79^\circ$ allows us to observe this object at SAO at all dates being at a zenith distance of less than 57°.

Preliminary results of multi-color photometry of the GRB 970508 optical remnant were reported elsewhere (Sokolov et al. 1997). In this paper we report the results of BVR_cI_c photometry from May to August 1997 discussing the correlation between the features of the optical light curves and those observed at other wavelengths. The second section deals with the search and detection of this optical source with the SAO telescopes and describes the BVR_cI_c photometry with the 1-m and

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Table 1. First week observations of GRB 970508 optical remnant.

night	UT (May)	telescope	B (s)	V (s)	R_c (s)	I_c (s)
09/10	09.75	1-m			300	
-”-	09.85	-”-			600	
10/11	10.77	6-m	300	200	100	300
-”-	10.93	-”-	300	200	100	300
11/12	11.76	-”-	450	300	150	450
12/13	12.87	-”-	450	600	150	900
13/14	13.88	-”-	1200	600	450	450

Table 2. Secondary photometric standards in the OT GRB 970508 field.

#	α_{2000}	δ_{2000}	B	V	R_c	I_c
1	06:53:37.19	79:17:30.7	20.44	19.14	18.31	17.53
2	06:53:36.30	79:15:30.0	19.93	19.17	18.71	18.27
3	06:53:39.23	79:15:21.1	17.94	17.40	17.06	16.71
4	06:53:48.50	79:16:32.7	21.93	20.43	19.49	18.53

6-m telescopes. The third section is dedicated to the results of CCD photometry in the phase of the source brightness maximum and to the following brightness fading in different filters up to the 87th day after the burst. The fourth section is dedicated to the discussion of the results and to the comparison of the optical light curves with those in X-ray and radio.

2. GRB 970508 optical counterpart search

The alert of a new GRB detection by BeppoSAX reached SAO only 3.5 hours after the high energy event (May 8.904 UT). Due to morning twilight, follow-up observations could start at the 1-m telescope on May 9.74 UT. The $5'$ WFC error box was completely covered with the CCD mosaic of 29 images in R_c band with 300 and 600 sec exposure times. The 1-m (Zeiss-1000) telescope is equipped with a CCD photometer ISD015A, 520×580 pixels corresponding to the field of view $2.'0 \times 3.'6$. The images from the 1-m telescope were compared to the corresponding fields of the Digitized Sky Survey (DSS). No new bright object was found up to the DSS limit for this field.

On the next night, May 10/11, a refined WFC error circle position was available: $\alpha_{2000} = 06^h53^m28^s$; $\delta_{2000} = +79^o17'.4$ with a $3'$ error radius (99% confidence level). Photometric observations of GRB 970508 field were then continued with the 6-m telescope. The 1040×1160 pixel CCD chip “Electron ISD017A” installed at the Primary Focus has a field of view of $2.'38 \times 2.'66$. A 2×2 binning mode was employed, so that each of the 520×580 zoomed pixels has angular size of $0.''274 \times 0.''274$. The gain is $2.3e^-$ per DN (Data Number). The readout noise is about $10e^-$.

The first image at the 6-m telescope was obtained on May 10.76 UT and a variable object was discovered by comparison with the image taken the night before. Its brightness, from May 9.85 UT to May 10.76 UT, increased of about 1.5 magnitudes. This object was first reported by Bond (1997) as a possible optical counterpart of GRB 970508 and was independently found in our data only about 0.5 day later. The summary of the observations carryed out at SAO during the first week after the GRB is reported in Table 1. The exposure times in seconds are shown for each filters.

Observations were carried out with filters closely matching the BVR_cI_c Johnson-Kron-Cousins system. The data were processed using the ESO-MIDAS software. Standard data reduction includes bias subtraction, flat-fielding and cosmic particle traces removal. Photometric conditions remained stable during two nights of May 13/14 and May 21/22.

Four bright stars (Fig. 1) in the GRB 970508 field were used as secondary photometric standards. Magnitudes of these stars were determined on the night of May 13/14 with good photometric conditions using four standard stars in the field of PG1657+078 (Landolt, 1992). Zero-point errors are better than 0.05^m. Coordinates and magnitudes of secondary photometric standards are given in Table 2. Our R_c magnitudes of stars 2, 3, 4 are 0.20 ± 0.01 higher than the magnitudes measured by Schaefer et al. (1997). The application of the analogous photometric procedure in BVR_cI_c Johnson-Kron-Cousins system, used at SAO RAS, is given in details in the paper by Kurt et al. (1998).

3. The brightness maximum phase and following source fading

We define as *source brightness maximum phase* the period when the optical object brightness increased to the maximum (or close to the maximum) and then began to drop down to $V \approx 21.5$ and $R_c \approx 21.1$. It corresponds approximately to the first week of observations after the GRB when the optical source could still be observed with many telescopes - big and medium ones. The results of the observations performed during these nights at SAO together with those from Palomar and Loiano are shown in Fig. 2. Many more observations other than those from Palomar and Loiano were performed, but the different photometric systems used and relatively smaller accuracy of the measurements do not allow a better evaluation of the OT behavior.

Johnson-Kron-Cousins magnitudes in the BVR_cI_c bands with the associated errors for GRB 970508 optical counterpart are given in Table 3. Given the BeppoSAX/GRBM trigger time t_0 = May 8.904 UT, we note (see Fig. 2):

1) from $t - t_0 = 0.226$ to $t - t_0 = 0.944$ the R_c brightness of the object seems to remain constant (Castro-Tirado et al. 1997; Djorgovski et al. 1997);

2) from $t - t_0 = 0.944$ to $t - t_0 = 1.866$ the R_c brightness increased of 1.5 mag. The magnitude increase rate using our 1-m data and the data from Palomar (Djorgovski et al. 1997) was about 0.12 mag per hour;

3) at $t - t_0 = 1.866$ the R_c magnitude reached the brightness maximum of 19.70 and from that date a decline of brightness began;

4) the magnitude decrease during the beginning (2–5 days) of the fading phase follows an exponential law in all four bands:

$$B = 19.689(\pm 0.036) + 0.452(\pm 0.014)(t - t_0)$$
$$V = 19.264(\pm 0.053) + 0.449(\pm 0.020)(t - t_0) \quad (1)$$

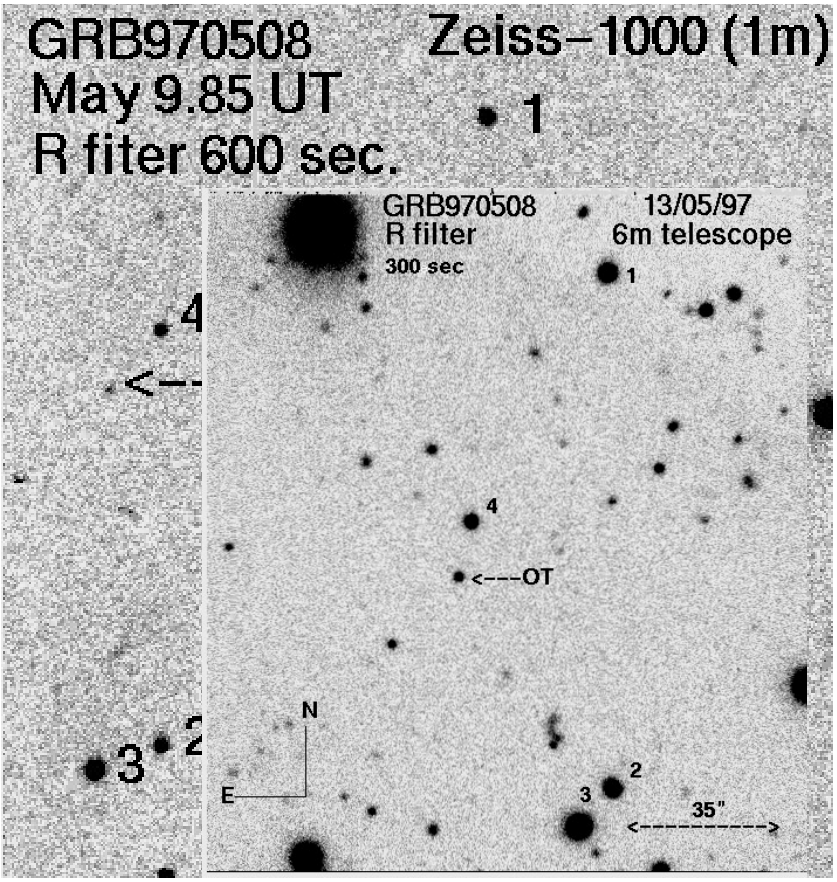

Fig. 1. The field near the optical source of GRB 970508 imaged with the 1-m telescope (before the maximum of the transient brightness) and with the 6-m telescope (the 4th night after the maximum) in R_c band. The object brightness in both images corresponds to $R_c \approx 21.1$. The stars – secondary photometric standards – are indicated.

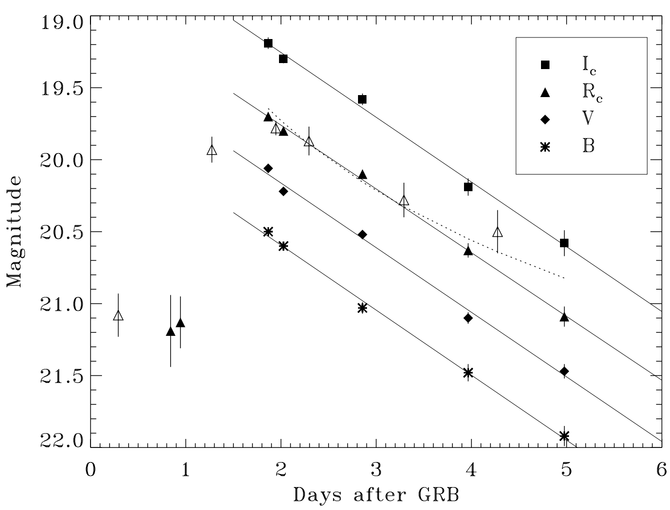

Fig. 2. The light curves of GRB 970508 optical counterpart during 5 days after the burst. SAO RAS (filled symbols), Loiano (Mignoli M. et al. 1997, $t - t_0 = 1.95$) and Palomar (Djorgovski et al. 1997, transformed to $R_c = r - 0.34 + A_r$) (open triangles) magnitudes with their errors are shown. Lines correspond to Eqs. (1) of exponential decline of brightness reported in the text. For R_c also the best fit power law is shown (dotted line).

$$R_c = 18.874(\pm0.029) + 0.443(\pm0.011)(t - t_0)$$
$$I_c = 18.355(\pm0.050) + 0.450(\pm0.019)(t - t_0)$$

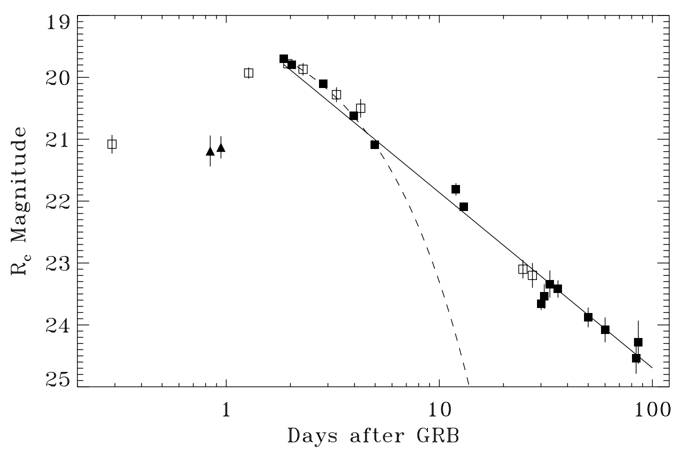

Fig. 3. R_c light curve of the optical counterpart of GRB 970508 during ≈ 86 days after the burst. SAO RAS (filled marks) and Palomar (Djorgovski et al. 1997), Loiano (Mignoli et al. 1997), HST (Fruchter et al. 1997), Keck II (Metzger et al. 1997) (open squares, transformed from Schaefer's photometric system to ours) magnitudes are shown. Lines correspond to power (up to $t - t_0 = 83.940$) and exponential law (dashed) for fading brightness.

A power law did not fit the data for the brightness fading after the maximum. For example for the R_c data it is $\chi^2_n = 0.97$ for the exponential fit while it is $\chi^2_n = 4.5$ for the power law. All the R_c data from $t - t_0 = 1.866$ to $t - t_0 = 4.976$ (10.77 UT – 13.88 UT) are used: SAO, Loiano and Palomar.

Table 3. GRB 970508 OT photometry results

UT	$t-t_0$	B	V	R_c	I_c
9.75 May	0.841			21.19 ± 0.25	
9.85	0.944			21.13 ± 0.18	
10.77	1.866	20.50 ± 0.03	20.06 ± 0.03	19.70 ± 0.03	19.19 ± 0.04
10.93	2.026	20.60 ± 0.03	20.22 ± 0.03	19.80 ± 0.03	19.30 ± 0.03
11.76	2.856	21.03 ± 0.04	20.52 ± 0.03	20.10 ± 0.03	19.58 ± 0.04
12.87	3.966	21.48 ± 0.06	21.10 ± 0.04	20.63 ± 0.05	20.19 ± 0.06
13.88	4.976	21.92 ± 0.07	21.47 ± 0.05	21.09 ± 0.07	20.58 ± 0.09
20.795	11.891		22.10 ± 0.18		
20.875	11.971			21.81 ± 0.10	
20.970	12.066				21.27 ± 0.13
21.892	12.988	23.12 ± 0.35		22.09 ± 0.07	
21.908	13.004		22.18 ± 0.14		
21.942	13.038				21.96 ± 0.13
07.917 Jun.	30.085			23.66 ± 0.10	
08.964	31.060	24.65 ± 0.25			
08.980	31.075		23.84 ± 0.24		
08.991	31.087			23.54 ± 0.20	
10.928	33.024			23.34 ± 0.22	
10.940	33.036		24.08 ± 0.25		
10.945	33.041				23.09 ± 0.35
13.954	36.050	24.62 ± 0.14			
13.966	36.061			23.42 ± 0.14	
13.992	36.088				23.30 ± 0.35
27.865	49.961	24.50 ± 0.22			
27.873	49.969		24.17 ± 0.16		
27.893	49.989			23.88 ± 0.16	
27.910	50.006				23.05 ± 0.14
07.946 Jul.	60.042	25.07 ± 0.21	24.62 ± 0.25	24.08 ± 0.20	
07.961	60.057				23.10 ± 0.15
31.843	83.940			24.54 ± 0.25	
31.857	83.952		24.60 ± 0.24		
31.862	83.958				23.08 ± 0.23
02.807 Aug.	85.902			24.28 ± 0.35	
02.825	85.920		24.59 ± 0.25		
02.855	85.950	25.32 ± 0.25			
03.989	87.085				23.04 ± 0.14

The spectrum of the object was close to a power law and its slope $F_\nu \propto \nu^{-1.2}$ did not change in time, with

$$(B-V) = 0.43, \;\; (V-R_c) = 0.39, \;\; (R_c-I_c) = 0.52$$

Taking into account galactic absorption $E(B-V) = 0.03$ gives

$$F_\nu \propto \nu^{-1.1}$$

and the following color indeces:

$$(B-V)_0 = 0.40, \;\; (V-R_c)_0 = 0.37, \;\; (R_c-I_c)_0 = 0.50$$

After the 5th day the decline of brightness is slowed down. In the BVR_c bands during about 85th day and I_c band until the $\approx$ 36th day, the light curve can be described by a power-law relation,

$$\begin{aligned} B &= 19.713(\pm 0.139) + 3.000(\pm 0.048) \times \log(t-t_0) \\ V &= 19.323(\pm 0.135) + 2.860(\pm 0.046) \times \log(t-t_0) \\ R_c &= 18.865(\pm 0.092) + 2.927(\pm 0.031) \times \log(t-t_0) \\ I_c &= 18.313(\pm 0.151) + 2.961(\pm 0.066) \times \log(t-t_0) \end{aligned} \quad (2)$$

with

$$\alpha_B = -1.200(\pm 0.019)$$

$$\alpha_V = -1.144(\pm 0.018)$$

$$\alpha_{R_c} = -1.171(\pm 0.012)$$

$$\alpha_{I_c} = -1.184(\pm 0.026),$$

neglecting the fact that for the first 5 days the light curve decay is better described by the exponential law in all the 4 bands. Fig. 3 shows this averaged power-law light curve for the R_c band up to about 84 days ($t-t_0 = 83.940$) after the burst.

Starting from the $\approx$ 36th day after the burst, the object did not show the further fall of the brightness in the I_c filter up to $t-t_0 = 87.085$. The magnitude of the object in the I_c filter in that period was stable around $I_c = 23.07$. Fig. 4a shows the light curves in the BVR_cI_c bands up to day 87.085.

4. Discussion. Comparison of optical, X-ray and radio brightness curves

The data obtained with the SAO RAS 1-m and 6-m telescopes allow us to divide the GRBR970508 brightness change curve into three stages (Figs. 2, 4 and Table 3):
1) the increase of brightness on time scale of about one day;
2) the exponential brightness fall during about 4 days with a stable broadband power-law spectrum;
3) the further brightness fading according to a power law.
Nevertheless, from the 36th day after the burst the object did not show the further fall of the brightness in the I_c filter. After 87 days, the deviation from the average power law (2) achieved already ≈ 1 mag.

As Fig. 3 shows, our observations with the 6-m telescope alone can be approximately described by a single law in the R_c filter, but in the phase of brightness maximum (Fig. 2), when all fluxes were measured with the smallest errors, we see the same deviations from the “average” power law in **all** 4 bands. Garsia et al. (1997) also mention that the brightness fading after the maximum cannot be well described by a single power law.

As discussed by Piro et al. (1998), after about 30 seconds from the high energy event, the GRB 970508 X-ray flux began to fall according to a power law with a slope of -1.1 ± 0.1. Nevertheless, in about 16.6 hours after the GRB the flux decay showed a temporal behavior analogous to the optical one during the first hours after the GRB (Pedersen et al. 1998). (We did not observe at that time, but in the R band the optical flux was either stable or showed a slow decrease in the first 8 hours after the GRB.) The features of the optical curves immediately after the maximum (May 10.77 UT) correlate with those of the X-ray transient light curve (Piro et al. 1998).

In Fig. 4 the SAO RAS BVR_cI_c brightness curves are presented together with the radio at 8.46 GHz (Frail et al. 1997) and the X-ray (BeppoSAX NFIs, Piro et al. 1998). Apparently, the most interesting moment in this phase was the sharp fall of the X-ray flux and its subsequent fast increase which was observed in details in the BeppoSAX MECS range 2–10 keV, but unfortunately no simultaneous optical observations were performed. The subsequent optical brightness increase which was observed also at SAO (Fig. 2) began with a small (≈ 5.5 hours) delay. (Though now it can be supposed that before that moment there was a genuine optical brightness minimum missed by the observers.) Piro et al. (1998) notice that the following behavior of X-ray flux deviates from the power law. In the X-ray range this deviation, lasting about 4 days, took about 30% of the energy released in the “afterglow” part of the power-law drop. It is about 10% of the gamma-ray energy itself. During the same period the optical decay does not follow a power-law too, but the exponential one (Figs. 2 and 3). This is in favor of a common origin of the X-ray and optical events. Taking into account the ratio of X-ray to optical flux during the 4 days after the optical maximum, more than 16% of the energy of the GRB event itself was released in optical together with X-rays. Thus, it is believable indeed that the energy of the GRB remnant is not only determined by the afterglow, but there is also an intrinsic burst activity of the source which has an energy comparable to that of the burst in a time scale 10.000 times longer than the duration of the GRB itself.

When comparing the radio and optical behavior of the source (Frail et al. 1997; Taylor et al. 1997) after the *brightness maximum phase*, the attention is immediately drawn to the fact that the decrease of the “twinkling” amplitude of the point-like radio source begins approximately from the 35th day. The radio fluxes in 8.46 and 4.86 GHz VLA bands show the tendency to stabilization. The stabilization of the radio fluxes began approximately at the same time of the deceleration fading we see in the I_c filter (≈ 8000 Å). The “radio plateau” was lasting till about the 65th day after the GRB. Then the flux decreased at both frequencies to ~ 0.4 mJy by the 87th day. (The flux in the 1.43 GHz band also approached the same value.) Thus, in spite of sharp flux variations in the beginning of observations, about one month after the burst the radio source considerably calms.

We note here that HST/NIMCOS flux measurements (Pian et al. 1998) in H band gave 6.2 ± 1.5 μJy, and not 3 ± 1 μJy, as was expected for power-law brightness fading in ground-based I and K bands. It was necessary to extrapolate these data to the H band assuming the same power-law spectrum slope which was observed in the brightness maximum phase (Metzger et al. 1997a; Sokolov et al. 1997). We note that the date of the HST observation and this deviation from the expected averaged power law in the HST/NIMCOS H band are close to the beginning of the deviation from the power law decay in our I_c band (Fig. 4) and to the “twinkling” amplitude decreasing date of the point-like radio source.

Pedersen et al. (1998) were the first to report about the deviation from the average power law. These authors find $R = 24.28 \pm 0.10$, 96 days after the high energy event, which gives a deviation from the power law decay of ≈ 0.6 mag. From the HST observation (on June 2, 1997) we see that the object retained the point-like appearance with a possible contribution of an underlying “compact galaxy” with FWHM = $0''.15$ and with $R \geq 25.4$. The possible deceleration of brightness fading rate in HST/NIMCOS H band and the observed flattening of the light curve in the I_c filter 36 days after the GRB might be interpreted as a sign of the detection of such a galaxy. (This would imply a quite red object for $z = 0.835$, but we do not discuss this implication in this work.)

On the other hand, the multi-wavelenght (optical, X-ray, radio) behavior we observe can also be explained by some intrinsic features of GRB 970508 OT, rather than by the manifestation of an host galaxy. For example, it is possible to suppose that we observe the formation of a jet-like structure related to the activity of a stellar mass compact object, i.e. a *gamma-ray burster*. The possibility of explanation of all the observational data by the intrinsic features of the source in the model of asymmetrical relativistic jets is now actively discussed (Dar 1997; Paczyn’ski 1997).

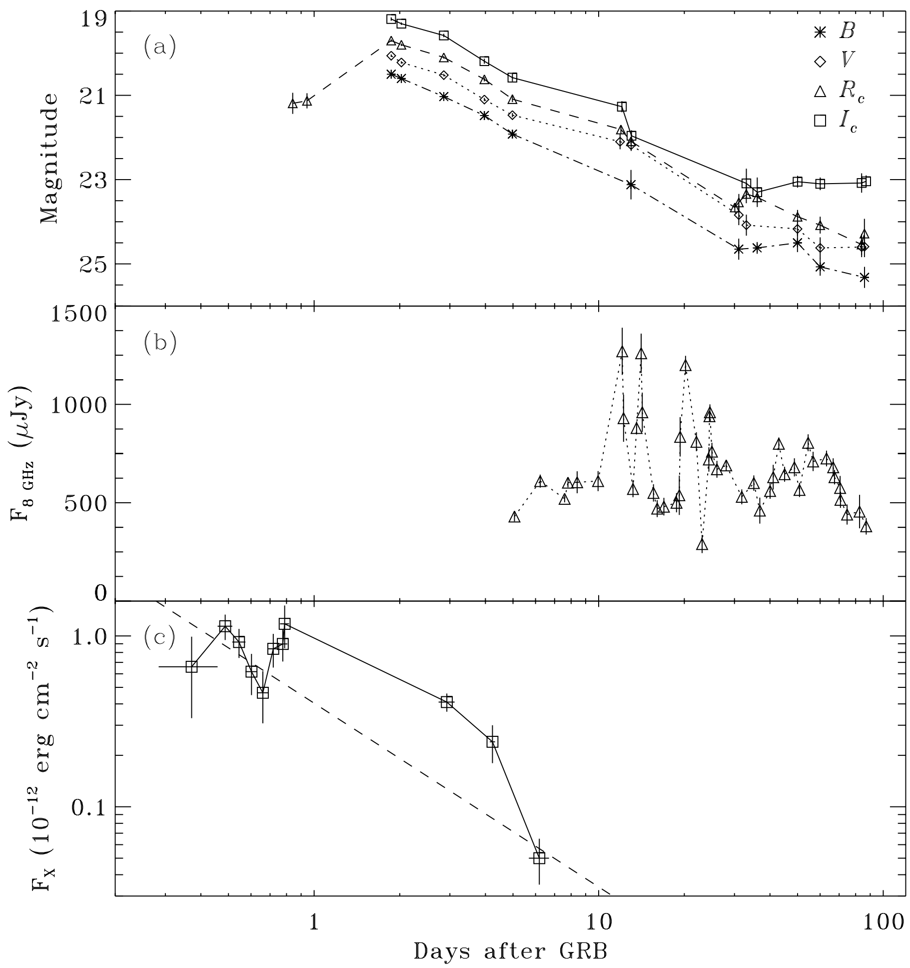

Fig. 4. GRB 970508 light curves: **a** BVR_cI_c SAO RAS data; **b** VLA/VLBA 8.46 GHz data (Frail et al. 1997); **c** 2–10 keV BeppoSAX MECS X-ray data with the $t^{-1.1}$ decay law (Piro et al. 1998). The power law with the slope of -1.1 is shown (dashed line).

5. Summary

The variable optical source associated to GRB 970508 was observed with the 1-m and 6-m telescopes of SAO RAS from May 9 to August 4, 1997. The details of temporal changes of brightness in the BVR_cI_c bands were compared with observations in X-ray and radio bands. We confirm the burst activity of the object detected by Piro et al. (1998) in X-rays in the first week after the high energy event. We notice also that the further brightness fading of the point-like object deviates from the average power law. This behavior was clearly seen at ≈ 8000 Å when, approximately 36 days after the GRB, a period of constant brightness starts.

Taking into account the global multi-wavelength behavior of GRBR 970508, it is presumable that the burst activity and subsequent deceleration of the brightness fading of the optical stellar-like source is caused by some intrinsic features of the object itself. Alternatively we probably observe the displaying of a dwarf underlying host galaxy with $I_c \approx 23.1$. To be certain of the absence of appreciable variability of a conjectural constant source further observational monitoring of a "quiet state" of the GRBR 970508 could give crucial inputs to the solution of this mystery.

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