$BV R_c I_c$ photometry of the GRB 980703 and GRB 990123 host galaxies

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Abstract. We present a photometry of GRB 980703 and GRB 990123 host galaxies which was performed about 20 days and a half year after gamma-ray bursts occured, respectively. The contributions of the optical transients (OT) were negligible in both cases. We derived broad band $BV R_c I_c$ spectra of the host galaxies and compared them to continuum spectra of different Hubble-type galaxies and averaged spectra of starburst galaxies. For $H_0 = 60 \text{ km s}^{-1}\text{Mpc}^{-1}$ and three Friedmann cosmological models with matter density and cosmological constant parameters $(\Omega_m, \Omega_\Lambda) = (1, 0), (0, 0), (0, 1)$ we estimated $M_{B,\text{rest}}$ and star-forming rates (SFRs) using the fluxes in photometric bands for the host galaxies. Within the range of cosmological parameters our estimates of the absolute magnitudes are: $M_{B,\text{rest}} = -20.60 \pm -21.73$ for the GRB 980703 host galaxy and $M_{B,\text{rest}} = -20.20 \pm -21.82$ for the GRB 990123 host galaxy. We obtained estimates of K-correction values and absolute magnitudes of the host galaxies using SEDs for star-forming galaxies.

Key words: gamma-rays: bursts: cosmology: observations – photometry: individual (GRB 980703, GRB 990123): galaxy – starbursts

1. Introduction

The origin of cosmic $\gamma$-ray bursts (GRBs) is still one of the outstanding problems in modern astronomy. Recently the study of GRBs has been revolutionized by the discovery of X-ray (Costa et al. 1997), optical (van Paradijs et al. 1997) and radio transients (Frail et al. 1997). The follow-up of optical transients (OT) resulted in the majority not only with OTs’ light curves but also their redshift measurements and the detection of GRB hosts. By now about 15 optical afterglows have been detected, almost all within a fraction of an arc second of very faint galaxies, with typical R-band magnitudes of 22-26 and over. About 10 redshifts have been measured in the range from $z = 0.6$ to $z = 3.4$. The long duration GRBs appear to be associated with star forming regions in the galaxies. The studies of the host galaxies and their properties advance understanding of the nature of the progenitor systems. In some proposed models an association of bursts with explosions of massive stars become popular (see ref. Paczynski, 1999 and MacFadyen A. & Woosley S. E., 1999 and references therein).

Here we report our direct $BV R_c I_c$ imagings of the GRB 980703 optical counterpart which were obtained after observations of Bloom et al. (1998). The latest observations of this object were obtained in the infrared $JHK$ bands by Bloom et al. (1998) In the case of the GRB 990123 host galaxy our $BV R_c I_c$ observations are the latest. In this paper we compare the $BV R_c I_c$ spectra of the GRB 980703 and GRB 990123 host galaxies with spectral energy distributions of normal galaxies of different Hubble types and extend the comparison to averaged spectra (SEDs) of S1 and S2 star-forming galaxies (Connoly et al., 1995). We obtained estimates of K-correction values and absolute magnitudes of the host galaxies using spectra of normal Hubble-type galaxies and SEDs for star-forming galaxies. Rough estimates of low limits for star-forming rates (SFR) in the GRB 980703 and GRB 990123 host galaxies were performed using the continuum luminosity at $\lambda = 2800\AA$ by extrapolating for the GRB 990123 host galaxy between $R_c$ and $I_c$ bands and by value of the flux in the $V$ band for the GRB 980703 host galaxy.
2. Observations and data reduction

Observations of the host galaxies of GRB 980703 and GRB 990123 were performed using the primary focus CCD photometer of the 6m telescope of SAO RAS. It was carried out with the standard (Johnson-Kron-Cousins) photometric $BVRcIc$ system. The direct $BVRcIc$ images for the GRB 980703 host galaxy are given in http://www.sao.ru/~sokolov/GRB/980703.html Table 1 presents the summary of observations. We performed photometric calibrations using the Landolt standard fields (Landolt, 1992): PG1633, PG1657, PG2331, PG2336 for the host galaxy of GRB980703, and PG2213, SA110 for the host galaxy of GRB990123. To estimate the Milky Way redenning for the host galaxy of GRB980703, we used extinction values from Cardelli, Clayton & Mathis (1989). We derived $0^{m}.251$, $0^{m}.188$, $0^{m}.141$ and $0^{m}.090$ in our photometric bands $BVRcIc$ respectively. Our direct $BVRcIc$ imagings of the GRB 980703 optical counterpart were obtained after observations of Bloom et al. (1998) on July 18 UT. The most recent observations of this object were obtained in the infrared $JHK$ bands by Bloom et al. (1998) on August 7 UT. In the case of the GRB 990123 host galaxy our $BVRcIc$ observations are the latest. We consider that the continuum was expected with minimum change due to the fading of the OT.

3. Cosmological models

The estimate of intrinsic physical parameters of extragalactic objects with redshifts approaching 1 depends considerably on the adopted cosmological model. The standard Friedmann model contains three parameters: Hubble constant $H_0$, matter density parameter $\Omega_m$, and cosmological constant parameter $\Omega_\Lambda$. Recent studies of the Hubble constant put it within the range $50 - 70$ km s$^{-1}$ Mpc$^{-1}$ (see Theureau et al. 1997). In this paper we adopt $H_0 = 60$ km s$^{-1}$ Mpc$^{-1}$. The values of $\Omega_m$ and $\Omega_\Lambda$ are observationally less constrained. The recent work on the $m - z$ test with supernovae of type Ia at redshifts up to 1 by Garnavich et al. (1998) make it imperative to consider in addition to the standard inflationary model also an empty universe with a cosmological constant. For a review of modern cosmological models and the necessary mathematical relations, see Baryshev et al. (1994). Here we use three Friedmann models which conveniently limit reasonable possibilities:

\[ H_0 = 60 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 1, \Omega_\Lambda = 0 \quad (A) \]

\[ H_0 = 60 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0, \Omega_\Lambda = 0 \quad (B) \]

\[ H_0 = 60 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0, \Omega_\Lambda = 1 \quad (C) \]

For these models the relation $\Omega_m + \Omega_\Lambda + \Omega_k = 1$ is valid, where $\Omega_m = \rho_08\pi G/3H_0^2$, $\Omega_\Lambda = \Lambda c^2/3H_0^2$, and $\Omega_k = -kc^2/R_0^2H_0^2$. Here $\rho, \Lambda, k$, and $R$ are density, cosmological constant, curvature constant, and radius of curvature, respectively, and “0” denotes the present epoch.

The luminosity distance $R_{\text{lum}}$, the angular size distance $R_{\text{ang}}$ and the proper metric distance $R_p$ are connected by the relation:

\[ R_{\text{lum}} = R_{\text{ang}}(1 + z)^2 = R_p(1 + z) \quad (1) \]

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Table 1: Photometry of the host galaxies of the GRB 980703 and GRB 990123

| Host       | Date UT  | Band | Exp. (s) | Magnitude, obs | Seeing |
|------------|----------|------|----------|----------------|--------|
| GRB 980703 | 24.05 Jul. 1998 | $B$  | 480      | $23.40 \pm 0.12$ | $1''.3$ |
|            | 24.06 Jul. | $V$  | 320      | $22.85 \pm 0.10$ | $1''.2$ |
|            | 24.06 Jul. | $R_c$ | 300      | $22.44 \pm 0.08$ | $1''.2$ |
|            | 24.07 Jul. | $I_c$ | 360      | $22.26 \pm 0.18$ | $1''.2$ |
| GRB 990123 | 8.85 Jul.  | $B$  | 600      | $24.90 \pm 0.16$ | $1''.5$ |
|            | 8.86 Jul.  | $V$  | 600      | $24.47 \pm 0.13$ | $1''.3$ |
|            | 8.84 Jul.  | $R_c$ | 600      | $24.47 \pm 0.14$ | $1''.1$ |
|            | 8.87 Jul.  | $I_c$ | 600      | $24.06 \pm 0.3$  | $1''.3$ |

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1. This paper gives more accurate $BVRcIc$ values with the UT dates (corresponding to Table 1) of observations for the host galaxy of GRB 980703 unlike the preliminary $BVRcIc$ values given in GCN notice #147.
where the proper distances for the adopted models are given by

\[ R_p = \begin{cases} R_H^2 \left( \frac{2(z-\sqrt{1+z^2})}{1+z} \right) & \text{for model A}, \\ R_H^2 \left( \frac{z(1+z^2)}{1+z} \right) & \text{for model B}, \\ R_H z & \text{for model C}. \end{cases} \]  

Here \( R_H = c/H_0 \) is the present value of the Hubble radius.

The absolute magnitude \( M(i) \) of the source observed in filter \((i)\) can be calculated from the magnitude-redshift relation

\[ M(i) = m(i) - K(i)(z) - 5 \log(R_{\text{turn}}/\text{Mpc}) - 25 \quad (3) \]

where \( m(i) \) is the observed magnitude of the object in the photometric band system \((i)\) and \( K(i)(z) \) is the K-correction at redshift \( z \), calculated from the rest-frame spectral energy distribution.

The linear size \( l \) of an object having an angular size \( \theta \) is given by

\[ l = \theta R_{\text{ang}} = \theta R_p/(1+z) \quad (4) \]

The K-correction in Eq. (3) can be calculated from the standard formula (Oke & Sandage 1968):

\[ K(i)(z) = 2.5 \log(1+z) + 2.5 \log \left( \int_{0}^{\infty} F_{\lambda} S_{i}(\lambda) d\lambda \right) + 2.5 \log \left( \int_{0}^{\infty} F_{\lambda} S_{i}(\lambda) d\lambda \right) \quad (5) \]

In this formula \( F_{\lambda} \) is the rest-frame spectral energy distribution, \( S_{i}(\lambda) \) is the sensitivity function for the filter \((i)\). For our photometric system we used sensitivity functions for \( BVR_cI_c \) filters from Bessel M. (1990).

### 4. Estimation of the K-corrections

The first spectral observations of the OT of GRB 980703 were obtained with the Keck-II 10-m telescope on UT 1998 July 07.6 and 19.6 (Djorgovski et al. 1998). Several strong emission lines were detected. These were [OIII], H\(\delta \), H\(\gamma \), H\(\beta \) and [OIII] with redshift \( z = 0.9662 \pm 0.0002 \). In addition, in the blue part of the spectrum some absorption features (FeII and MgII, MgI - absorption systems) with \( z = 0.9656 \pm 0.0006 \) were detected. In the case of the OT of GRB 990123 absorption lines were detected only (Kelson et al. 1999, Hjorth et al. 1999) with \( z_{\text{abs}} = 1.6004 \). The HST image reveals that the optical transient is offset by 0\('\)0.67 from an extended object (Bloom et al. 1999). This galaxy is most likely to be a host galaxy of GRB 990123 and source of the absorption lines of metals at redshift \( z = 1.6004 \).

In Figure 1 we compared the \( BVR_cI_c \) broad band spectra of the host galaxies of GRB 980703 and GRB 990123 with the spectral energy distributions of normal galaxies of different Hubble types (Pence, 1976). Table 2 presents fluxes of the host galaxies. Here we used the zero-points from Fukugita et al. (1995) for our photometric bands. For the GRB 980703 the host galaxy fluxes are presented according to dereddened magnitudes. For the GRB 990123 within our magnitude errors the Galactic reddening is negligible. The central \( \lambda_{\text{obs}} = \lambda_{\text{eff}} \) for our photometric system are equal correspondingly to: \( \lambda_B = 4448\AA \), \( \lambda_V = 5505\AA \), \( \lambda_R = 6588\AA \) and \( \lambda_I = 8060\AA \). FWHM are equal to: \( \Delta \lambda_B = 1008\AA \), \( \Delta \lambda_V = 827\AA \), \( \Delta \lambda_R = 1568\AA \), \( \Delta \lambda_I = 1542\AA \), respectively.

Using equation 3 and the spectral energy distribution of the Im Hubble-type galaxies we estimated the value of the K-correction for the magnitudes of the host galaxies of GRB 980703 and GRB 990123 according to \( z = 0.966 \) and \( z = 1.6 \), respectively. The estimated values of the K-correction in the \( B \)-band are \( K_B = 0.68 \) for the GRB 980703 host galaxy and \( K_B = 0.88 \) for the GRB 990123 host galaxy. In this case, the absolute magnitudes from equation 3 for the host galaxy of GRB 980703 are: \( M_{B\text{rest}} = -21.29 \) for model (A), \( M_{B\text{rest}} = -21.81 \) for model (B) and \( M_{B\text{rest}} = -22.42 \) for model (C). For the host galaxy of GRB 990123 in the same way absolute magnitudes are: \( M_{B\text{rest}} = -20.95 \) for model (A), \( M_{B\text{rest}} = -21.77 \) for model (B) and \( M_{B\text{rest}} = -22.57 \) for model (C).

However, we consider it to be not quite correct to compare our broad band spectra to normal Hubble types of galaxies. Obviously the starburst activity may drastically change the spectral distribution towards the ultraviolet part of the spectrum. According to this consideration, we compared our \( BVR_cI_c \) spectra to the averaged spectral energy distribution of starburst galaxies from Connolly et al. (1995). Figure 2 and Figure 3 demonstrate a comparison of the starburst averaged spectral energy distributions to the \( BVR_cI_c \) broad band spectra of the host galaxies GRB 980703 and GRB 990123, respectively. The spectra of starburst were grouped according to increasing values of the color excess \( E(B-V) \): from S1, with \( E(B-V) = 0.05 \) to S6, with \( E(B-V) = 0.7 \) (Connolly et al. 1995). Using relation for \( \tau_B^{\text{obs}} \) (Balmer optical depth) from Calzetti et al. (1994) we derived the values of color excess for individual starburst galaxies. It
are $E(B-V) < 0.10$ for S1, $0.11 < E(B-V) < 0.21$ for S2, $0.25 < E(B-V) < 0.35$ for S3, $0.39 < E(B-V) < 0.50$ for S4, $0.51 < E(B-V) < 0.60$ for S5 and $0.61 < E(B-V) < 0.70$ for S6 (see Table 3 in Calzetti et al. 1994). In Figure 2 and Figure 3 the spectra of the S1 and S2 type galaxies was averaged with a 10 Å window.

In this case, the calculations of the K-corrections from equation 5 yield: $K_B = -0.01$ for the host galaxy of GRB 980703 and $K_B = 0.13$ for the host galaxy of GRB 990123. Then, the absolute magnitudes for the host galaxy of GRB980703 are: $M_{B,rest} = -20.60$ for model (A), $M_{B,rest} = -21.12$ for model (B) and $M_{B,rest} = -21.73$ for model (C). For the host of GRB990123 $M_B$ are: $M_{B,rest} = -20.20$ for model (A), $M_{B,rest} = -21.02$ for model (B) and $M_{B,rest} = -21.82$ for model (C).

5. Estimations of star-forming rate

We have roughly estimated also SFR using the continuum luminosity at $\lambda_{rest} = 2800$ Å (see Madau et al. 1998). In the calculations we assumed the cosmological models described above.

For the host galaxy of GRB 980703 the effective wavelength of the V band for $z = 0.966$ corresponds to 2800 Å in the rest frame. Using the flux in the V band we estimated SFR for the host galaxy of GRB980703: $SFR_{Salpeter} \approx 15 \pm 2 \ M_\odot \ yr^{-1}$, $SFR_{Scalo} \approx 23 \pm 2 \ M_\odot \ yr^{-1}$ for model (A); $SFR_{Salpeter} \approx$...
Figure 2: A comparison of the GRB 980703 host galaxy broad band rest-frame ($z = 0.966$) spectrum to spectrum of S2-galaxies $\log F_{\lambda} = \log F_{\lambda,S2} + C$ (see Connoly et al., 1995). FWHM of each filter for $\lambda_{eff}$ with the account for $z$ are denoted by dashed horizontal lines with bars.

Figure 3: A comparison of the GRB 990123 host galaxy broad band rest-frame ($z = 1.6$) spectrum to spectrum of S1-galaxies $\log F_{\lambda} = \log F_{\lambda,S1} + C$ (see Connoly et al., 1995). FWHM of each filter for $\lambda_{eff}$ with the account for $z$ are denoted by dashed horizontal lines with bars.

$24 \pm 2 \, M_\odot \, yr^{-1}$, $SFR_{\text{Scalo}} \approx 37 \pm 4 \, M_\odot \, yr^{-1}$ for model (B); $SFR_{\text{Salpeter}} \approx 43 \pm 4 \, M_\odot \, yr^{-1}$, $SFR_{\text{Scalo}} \approx 66 \pm 6 \, M_\odot \, yr^{-1}$ for model (C), where the index of Salpeter and Scalo denotes the Salpeter and Scalo initial mass function (IMF) (Madau et al. 1998).

To estimate SFR of the host galaxy of GRB 990123, we used the interpolated value of the flux at the wavelength 2800Å in the rest frame between $R_c$ and $I_c$ band. We assumed

$$\log F_{\nu,2800\AA} = -29.28 \pm 0.13 \frac{erg}{s \cdot cm^2 \cdot Hz}.$$  

The calculation yields: $SFR_{\text{Salpeter}} \approx 8 \pm 2 \, M_\odot \, yr^{-1}$, $SFR_{\text{Scalo}} \approx 12 \pm 4 \, M_\odot \, yr^{-1}$ for model (A); $SFR_{\text{Salpeter}} \approx 17 \pm 6 \, M_\odot \, yr^{-1}$, $SFR_{\text{Scalo}} \approx 25 \pm 9 \, M_\odot \, yr^{-1}$ for model (B); $SFR_{\text{Salpeter}} \approx 34 \pm 12 \, M_\odot \, yr^{-1}$, $SFR_{\text{Scalo}} \approx 54 \pm 17 \, M_\odot \, yr^{-1}$ for model (C).

Of course, these estimates are the lower limit to SFR because our calculations were performed without any galaxy rest-frame extinction correction. Moreover, uncertainties of our results are estimated formally from the errors of fluxes.
6. Discussion

Observations were carried out a significant time after the gamma-ray bursts. For the host galaxy of GRB 980703 it was about 20 days after the gamma-ray burst, and for the GRB 990123 host galaxy about half a year. This allows us to consider that the contribution of the optical transient is very small and we observed light only of the host galaxies.

As a discussion, it should be noted that there are uncertainties in the estimates of the absolute magnitudes of the host galaxies due to the K-correction. In the case of the host galaxy of GRB 990123 this uncertainty is about $1^m$, and in the case of the host of GRB 980703 it is about $0^m.7$. However, we consider that a more correct result is the value of $M_B$ according to the comparison to the starburst averaged spectra — $M_{B_{rest}} = -20.60, -21.12, -21.73$ for the host galaxy of GRB 980703 in (A), (B), (C) cosmological models respectively, and $M_{B_{rest}} = -20.20, -21.02, -21.82$ for the host galaxy of GRB 990123. Moreover, our $BVRcIc$ broad band spectra are better fitted by the S1 and S2 spectral energy distribution. To compare our results to the results of Bloom et al. (1998,1999) we assume a cosmology model with $H_0 = 65 km s^{-1} Mpc^{-1}, \Omega_m = 0.2$ and $\Omega_A = 0$. For the GRB 980703 host galaxy we used the value of the luminosity distance from Bloom et al. (1998), $d_L = 1.92 \times 10^{28} cm$. In the case of GRB 990123 host galaxy we used the value of the luminosity distance from Bloom et al. (1999), $d_L = 3.7 \times 10^{28} cm$. Calculations from equation 3 yield: $M_{B_{rest}} = -20.8$ and $M_{B_{rest}} = -20.62$ for the GRB 980703 and GRB 990123 host galaxies respectively, while the values of Bloom et al. are $-20.2$ and $-20.0$ for the GRB 980703 and GRB 990123 host galaxies, respectively. Note that the estimates of absolute magnitudes of Bloom et al. (1998, 1999) for the both host galaxies are performed in another way without the K-correction by fitting to the spectrum in the case of the GRB 980703 host galaxy and by interpolating between the observed the STIS and the $K$-band data points using a power law in the case of GRB 990123 host galaxy.

It should be noted that our estimates of the star-forming rate are higher than the estimates of Djorgovski et al. (1998) and Bloom et al. (1999). It is interesting that the for GRB 980703 host galaxy our flux at $\lambda = 2800\AA$ is $\sim 3.1 \mu Jy$ and is matching the value of the flux on July 7 from Djorgovski et al. (1998). Probably, the OT contribution was already negligible in the $V$ band on July 7. In the case of GRB 990123 host galaxy our value of the flux at $\lambda = 2800\AA$ was estimated by interpolation between observed points. However, the values of Bloom et al. (1999) are $0.17 \mu Jy$ (for $\beta = 0$) and $0.21 \mu Jy$ (for $\beta = -0.8$) while our ones are $0.52^{+0.18}_{-0.14} \mu Jy$. This discrepancy can be explain as follow. Our estimate of the flux was performed by interpolation between the $R_c$ ($\lambda_{eff} = 6588\AA$) and $I_c$ ($\lambda_{eff} = 8060\AA$) bands, while the values of Bloom et al. were interpolated with power law between STIS (approximately $V$ band, $\lambda_{eff} = 5505\AA$) point and $K$ band ($\lambda_{eff} = 2.195\mu m$). Moreover, Bloom et al. measured the flux of the host galaxy by masking sets of pixel dominated by the OT (Bloom et al. 1999) because observations in the $K$ band were carried out on epoch 9 and 10 February UT, 17-18 days after gamma-ray burst, (Bloom et al. 1999) when contribution of the OT was not negligible, while our observations was performed about a half year after gamma-ray burst occurred. Obviously, the our estimate is more exact than that of Bloom et al.

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