Bull. Spec. Astrophys. Obs., 2001, 51, 48-60

Modeling of GRB host galaxy spectra

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Received May 16, 2001; accepted June 7, 2001.

Abstract.
The modeling of spectral energy distributions of some galaxies, where GRBs were detected, was performed. The main parameters of these galaxies (with characteristic colour and spectral features of star formation burst): luminosity, mass, mean star formation rate and probable star formation scenario were determined taking into account an extinction by dust and gas. It was shown that these galaxies are usual ones with a higher star formation rate, which are mainly observed in optical at redshift about 1 and higher.

Key words: gamma rays: bursts — galaxies: evolution — galaxies: structure

1. Introduction

It seems that the main question, which excites investigators of cosmic gamma-ray burst (GRB) phenomenon (both theorists and observers), is "What kind of real astrophysical objects might be progenitors of GRB sources?" Behavior of optical afterglow light curves (Sokolov, 2001; Bjornsson et al., 2001; Bloom et al., 1999), detection of Fe absorption and emission lines in spectra of X-ray (e.g. Piro et al., 2000) afterglow and some evidence of connection between GRB and HII regions (e.g. Vreeswijk et al., 2001) in host galaxies make us to consider that long duration GRBs are close related to corecollapse Supernovae than to massive stars as progenitors. Moreover as was noted by Fruchter (2001), GRB hosts are quite blue as one would expect if GRBs were related to star formation, and, that is very important, positions of optical transient project on the star field of their host galaxies (Bloom et al., 2000a). It is worth to note that for redshift about 1 (median redshift for GRB host galaxies) in optical domain we observe rest-frame UV part of GRB host galaxy spectra, i.e., in fact, only emission from the star-forming regions. In couple with the projection of optical transients on their host galaxy this directly implies to connection of GRB with star formation in host galaxies. The connection with star formation implies that there is an extinction in GRB host galaxies. The estimates from the spectra of the host galaxies of GRB 980703 (Djorgovski et al., 1998) and GRB 990712 (Vreeswijk et al., 2001) show that the extinction may be significant ($A_V = 0.3 \pm 0.3$ in the first case and $A_V = 3.4^{+2.4}_{-1.7}$ in the latter). Thus, the extinction may sufficiently affect host galaxy parameters: luminosity, star formation rate, spectral energy distributions (SEDs).

We believe that study of GRB hosts galaxies helps us to shed light on the nature of GRB progenitors. In addition, as was shown by Blain & Natarajan (2000) and Ramirez-Ruiz et al. (2000) (and references therein), GRBs may be used as a probe of cosmic star formation in the Universe, and therefore properties of their host galaxies are very useful in cosmological studies.

Following this, we examine broad-band flux spectra of several GRB host galaxies. First, we use comparison of our broad-band flux spectra with templates of local starburst galaxies with known reddening (*a first approximation*). This is done in Sect. 3. These templates also allow us to estimate absolute magnitudes of the host galaxies making use of different methods. The results are given in Sect. 3. Second, bear in mind the derived rough estimates of reddening, we perform theoretical modeling of spectral energy distributions of the host galaxies and derive more exact estimates of reddening (*a second approximation*) as well as parameters of the hosts. In modeling we additionaly use already published near-infrared data. The results are presented in Sect. 4. Final discussion and conclusions are given in Sect. 5 and Sect. 6.

2. Observational data

Today there are 14 host galaxies with known redshifts. In Table 1 we present a summary of recent GRB host observational data. All magnitudes are corrected for Galactic extinction. In the third column of Table 1 we in addition mark the instruments where host galaxy magnitude was obtained. As can be seen the contribution of the 6 m telescope is very high. In Sect. 4 we will need to transform the magnitudes to the fluxes at the effective wavelength of the broad-band filters. Here we used the zero points of the bands from Fukugita et al. (1995).

3. Comparison with local starburst templates and absolute magnitudes

It would be of interest to compare our broad-band flux spectra to spectra of nearby starburst galaxies. Here we used templates of these galaxies from Calzetti et al. (1994). These templates were grouped according to increasing of values of the colour excess $E(B-V)$: from S1 with $E(B-V) = 0.05$ mag to S6 with $E(B-V) = 0.7$ mag. Using the relation for τ_B^l (Balmer optical depth) from Calzetti et al. (1994), we derived the values of colours excess for an individual group of starburst galaxies. These are: $E(B-V) < 0.10$ mag for S1, $0.11 < E(B-V) < 0.21$ mag for S2, $0.25 < E(B-V) < 0.35$ mag for S3, $0.39 < E(B-V) < 0.50$ mag for S4, $0.51 < E(B-V) < 0.60$ mag for S5 and $0.61 < E(B-V) < 0.70$ mag for S6 (see Table 3 in Calzetti et al. (1994)). It should be noted that these SEDs are not observed but are the templates that have been constructed using real observed starburst SEDs up to a redshift of $z \sim 0.03$ (Connoly et al., 1995).

The fluxes of the templates were integrated with transmission curves of the BVR_cI_c broad-band filters from Bessel (1990) and the derived fluxes at the effective wavelenghths of each filters were compared to the observed ones. For each group of the templates the value of χ^2 was computed. The results of comparison are given in Table 2. In the last column the label "$\chi^2/d.o.f.$" means the value of χ^2 divided by the degree of freedom. Figs. 1, 2 and 3 demonstrate the best fitting (minimum of $\chi^2/d.o.f$) of our broad-band spectra by the starburst template galaxies. However, we should note that in the case of the host galaxy of GRB 980703, an S2 template galaxy just roughly fitted the BVR_cI_c data. But, as will be shown in Sect. 4, the results of this comparison will allow us to derive a more exact fitting of the observational data by modeling. It should be noted that the spectrum of the host galaxy of GRB 970508 has no feature at 3200Å like the one seen in S5 (Connoly et al., 1995). But, we made an estimate of the contribution of this bump for the S5 template to the V and R_c bands and concluded that it is negligible.

The comparison with the templates allow us to estimate the absolute magnitudes of the host galaxies. Here we use a Friedman cosmological model with $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ (see e.g. de Bernardis et al. 2000). Recent studies of the Hubble constant put it within the range $50 - 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (see Theureau et al., 1997). In this paper we adopt $H_0 = 60\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. According to our definition of the spectral types of the host galaxies (S1, S2 ...), we can now estimate the K-correction (the definition of the K-correction was taken from Oke & Sandage, 1968). In Table 3 we present the K-correction and the corresponding absolute magnitudes of the host galaxies. For the host galaxies of GRB 970508 ($z = 0.835$) and GRB 991208 (z=0.7063) we give two additional estimates of K_B. As the I_c-band roughly corresponds to the B-band in the rest-frame, we can calculate directly from definition of the K-correction (Oke & Sandage, 1968) a second estimate of the K-correction for the B-magnitude, assum-

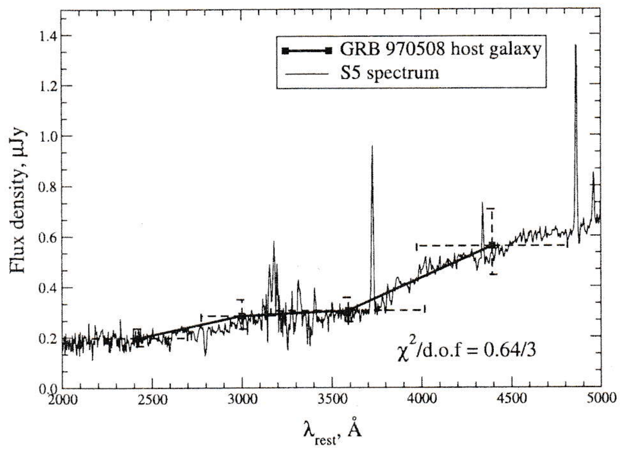

Figure 1: *The comparison of the BVR_cI_c broad-band rest-frame ($z = 0.835$) flux spectra of the host galaxy of GRB 970508 with S5 template. The SED of the template was scaled to obtain the best fit. Taking into account z, the FWHM of each filter for λ_{eff} is marked by dashed horizontal lines with bars.*

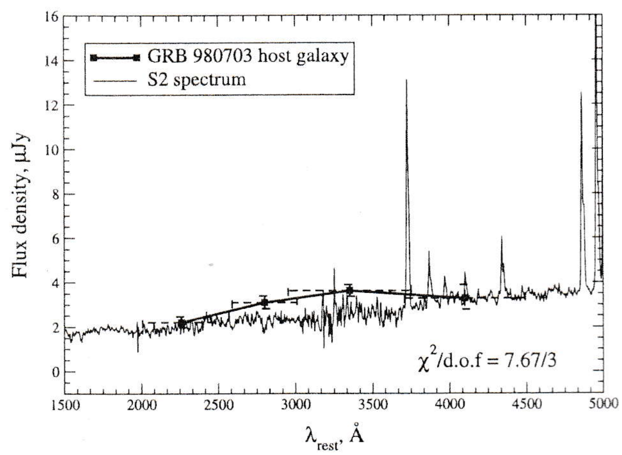

Figure 2: *The comparison of the BVR_cI_c broad-band rest-frame ($z = 0.966$) flux spectra of the host galaxy of GRB 980703 with S2 template.*

Table 1: *Photometry of 14 GRB host galaxies with known redshifts*

Host	Date UT	Band	Dereddened magnitude	Absolute magnitude ($M_{B_{rest}}$)
GRB 970228	01.35 Sep. 1998	B (VLT-UT1)	> 25.11	-18.6 ± 0.4
	04.71 Sep. 1997	V (HST/STIS)	25.04 ± 0.20	$-18.6 \pm 0.4^*$
	04.71 Sep.	R_c (HST/STIS)	24.68 ± 0.20	$-18.3 \pm 0.3^*$
	04.71 Sep.	I_c (HST/STIS)	24.38 ± 0.20	
GRB 971214	24.85 Jul. 1998	V (BTA)	25.38 ± 0.3	-21.1
	24.84 Jul.	R_c (BTA)	25.65 ± 0.3	$-21.7 \pm 0.5^*$
GRB 970508	21.74 Aug. 1998	B (BTA)	25.77 ± 0.19	-18.6 ± 0.3
	23.95 Jul. 1998	V (BTA)	25.25 ± 0.22	$-19.0 \pm 0.5^*$
	21.74 Aug.	R_c (BTA)	24.99 ± 0.17	$-18.6 \pm 0.2^*$
	23.95 Jul.	I_c (BTA)	24.07 ± 0.25	$-18.7 \pm 0.3^*$
GRB 980613	24.80 Jul. 1998	B (BTA)	24.77 ± 0.25	-20.8
	24.82 Jul.	V (BTA)	23.94 ± 0.21	$-20.2 \pm 0.8^*$
	23.00 Jul.	R_c (BTA)	23.58 ± 0.1	$-20.7 \pm 0.2^*$
GRB 980703	24.05 Jul. 1998	B (BTA)	23.15 ± 0.12	-21.3
	24.06 Jul.	V (BTA)	22.66 ± 0.10	$-22.1 \pm 0.6^*$
	24.06 Jul.	R_c (BTA)	22.30 ± 0.08	$-21.7 \pm 0.2^*$
	24.07 Jul.	I_c (BTA)	22.17 ± 0.18	$-21.0 \pm 0.2^*$
GRB 990123	8.85 Jul. 1999	B (BTA)	24.90 ± 0.16	-20.9
	8.86 Jul.	V (BTA)	24.47 ± 0.13	$-22.1 \pm 1.6^*$
	8.84 Jul.	R_c (BTA)	24.47 ± 0.14	$-20.9 \pm 0.3^*$
	8.87 Jul.	I_c (BTA)	24.06 ± 0.3	$-20.8 \pm 0.4^*$
GRB 990510	29 Apr. 2000	V (HST/STIS)	27.8 ± 0.5	$-18.8 \pm 1.7^*$
GRB 990712	29 Aug. 1999	V (HST/STIS)	22.40 ± 0.04	-19.9 ($-19.7 \pm 0.1^*$)
	29 Aug. 1999	R (HST/STIS)	21.72 ± 0.06	$-19.9 \pm 0.1^*$
GRB 991208	31.90 March 2000	B (BTA)	25.18 ± 0.16	-18.8 ± 0.3
	31.84 March	V (BTA)	24.63 ± 0.16	$-19.1 \pm 0.3^*$
	31.96 March	R_c (BTA)	24.36 ± 0.15	$-18.6 \pm 0.2^*$
	31.87 March	I_c (BTA)	23.70 ± 0.28	$-18.9 \pm 0.2^*$
	04.21 April	I_c (NOT)	23.28 ± 0.20	
GRB 991216	17.6 Apr. 2000	R (HST/STIS)	25.4 ± 0.2	$-18.7 \pm 0.4^*$
GRB 000131	5.03 March 2000	R (VLT)	> 25.6	$> -23.0^*$
	5.02 March	I (VLT)	> 24.7	$> -22.9^*$
GRB 000301C	19 April 2000	V (HST/STIS)	> 28.3	$> -19.0^*$
	19 April	R (HST/STIS)	> 27.8	$> -18.2^*$
GRB 000418	4.17 June 2000	R (HST/STIS)	23.8 ± 0.2	$-20.6 \pm 0.3^*$
GRB 000926	27 October 2000	R (NOT/ALFOSC)	23.8 ± 0.2	$-22.3 \pm 0.4^*$

* The estimates of the $M_{B_{rest}}$ were obtained using comparison with the local starburst templates by scaling them to corresponding observed V, R and I magnitude (see Sect. 3).

ing 2.5 $\log(F_{B_{rest}}/F_{\lambda_{B/(1+z)}}) \approx 2.5 \log(F_{I_{obs}}/F_{B_{obs}})$. Thus we derived: $K_B = 0.51 \pm 0.32$ mag and $K_B = 0.21 \pm 0.31$ mag for the host galaxies of GRB 970508 and GRB 991208, respectively. As a third estimate we can assume $K_B = 0.0$ mag considering that the observed I_c filter matches the B filter in the rest-frame. This differs from the other two estimates, since going from I_c to the B-band we have to take into ac-

Table 2: *The results of comparison with local starbursts*

Host	Template	$E(B-V)$	A_V^*	$\chi^2/d.o.f.$
GRB 970508	S5	0.51–0.60	1.58–1.86	0.64/3
GRB 980613	S6	0.61–0.70	1.89–2.17	1.22/2
GRB 980703	S2	0.11–0.21	0.34–0.65	7.67/3
GRB 990123	S1	<0.10	<0.31	2.29/3
GRB 991208	S5	0.51–0.60	1.58–1.86	0.99/3

* The values correspond to the Milky Way extinction law (Cardelli et al., 1989).

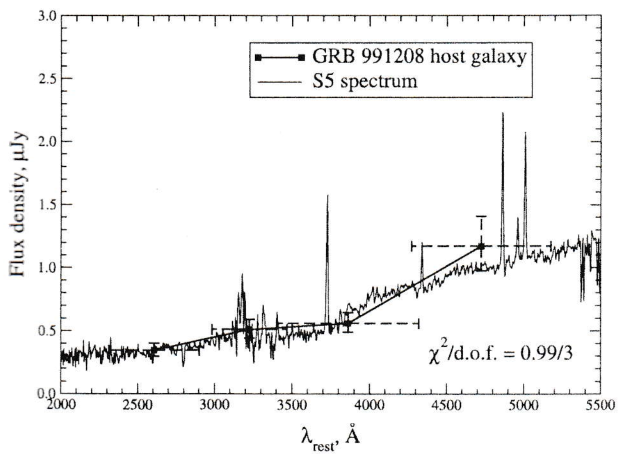

Figure 3: *The comparison of the BVR_cI_c broad-band rest-frame ($z = 0.706$) flux spectra of the host galaxy of GRB 991208 with S5 template.*

Table 3: *The K-corrections and absolute magnitudes of 5 GRB host galaxies*

Host	K_B-correction	Absolute magnitude $M_{B_{rest}}$
GRB 970508	0.44	−18.62
	0.51 ± 0.32	−18.69
	0.0 (I_c to B)	−19.88
GRB 980613	0.85	−20.76
GRB 980703	−0.01	−21.27
GRB 990123	0.13	−20.93
GRB 991208	0.46	−18.79
	0.21 ± 0.31	−18.54
	0.0 (I_c to B)	−19.81

count the mismatch of zero points and the transmission curves of the colour bands.

Using the result of the comparison with the local starburst templates we can conclude that broad-band flux spectra of GRB host galaxies are well approximated by these templates. This allow us to extend the sample of GRB host galaxies with the estimated absolute magnitudes. Using the S1, S2, S3, S4, S5 and S6 SEDs and scaling them, we can obtain estimates of the $M_{B_{rest}}$ from the observed V, R and I for the host galaxies from Table 1. In Table 1 the last column presents these estimates. The $M_{B_{rest}}$ is given oposite the observed host galaxy magnitude (V, R and I), which was used for $M_{B_{rest}}$ estimates. Opposite the observed B-band magnitude, we present the correct estimates of the $M_{B_{rest}}$ from Table 3 and of other authors (Bloom et al., 2000b for the host galaxy of GRB 970228; Kulkarni et al., 1998 for the host galaxy of GRB 971214; Hjorth et al., 2000 for the host galaxy of GRB 990712).

4. Modeling

As was noted above we, as a second approximation to estimate reddening in host galaxies, we performed theoretical modeling of the continuum spectral energy distribution of the host galaxies of GRB 970508 and GRB 980703. Note that for these galaxies the spectra BVR_cI_c and some near-infrared data are available and, what is most essential before drawing any conclusions, these galaxies have the lowest (GRB 970508) and the highest (GRB 980703) luminosities (see Table 3).

4.1. The method

We used the PEGASE code (**P**rojet d'**É**tude des **GA**laxies par **S**ynthèse **É**volutive) developed by Fioc & Rocca-Volmerange (1997), which is publicly available at `ftp://ftp.iap.fr/pub/from_users/fioc/PEGASE/PEGASE.2/`. We assumed the Salpeter initial mass function (IMF) with the low and high mass cut-offs to be 0.1 $M_\odot$ and 120 $M_\odot$, respectively. In the computations the $Z_\odot$ and $0.1Z_\odot$ metallicities were assumed as well as the simplest instantaneous burst and more complex exponential decreasing star formation. Since PEGASE computes output data in monochromatic luminosities, we used the cosmological parameters H_0=60 km s^{-1} Mpc^{-1}, Ω_M=0.3 and Ω_Λ=0.7 for transforming monochromatic luminosities into the observed fluxes.

The comparison of the BVR_cI_c broad-band flux spectra of the host galaxies with the local starburst SEDs allows us to consider that there is a signifi-

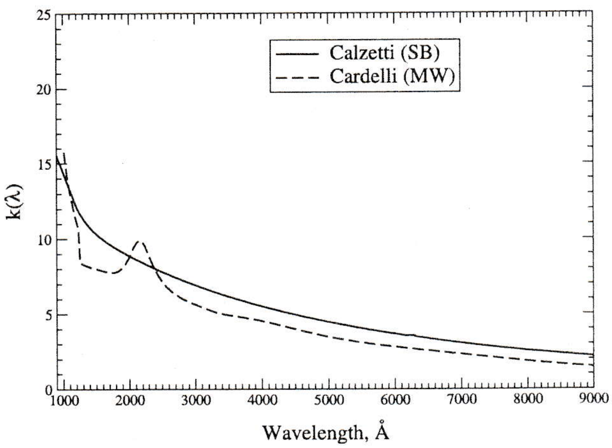

Figure 4: *Extinction curves $k(\lambda)$ for the Cardelli et al. (1989) and Calzetti et al. (2000) reddening laws. Cardelli et al. extinction law represents the reddening in Milky Way, while Calzetti et al. law was derived empirically from a sample of integrated spectra of starburst galaxies.*

cant internal extinction in the host galaxies. To estimate the influence of this important fact, we used the Cardelli et al. (1989) and Calzetti et al. (2000) extinction laws. These laws differ in the shape of the curve and the parameterization of $R_V \equiv A_V/E(B-V)$ with $R_V = 4.05$ for the Calzetti et al. law and $R_V = 3.1$ for the Cardelli et al. law. Fig. 4 shows both extinction law curves. Notice that the Cardelli et al. extinction law represents the reddening in the Milky Way (MW), while the Calzetti et al. law was derived empirically from a sample of integrated spectra of starburst galaxies (SB).

For simplicity we assumed a dust-screen model with the following mathematical relation for the reddening of spectra: $F_{\rm obs}(\lambda) = F_{\rm int}(\lambda)10^{-0.4A_\lambda}$, where $F_{\rm obs}$ and $F_{\rm int}$ are the observed and intrinsic fluxes, respectively, and $A_\lambda = k(\lambda)E(B-V)$ is the extinction at a wavelength λ.

To construct the theoretical template SEDs we applied a two-component model: the first component is a burst of star formation ("burst" component) and the second one is an old stellar population ("old" component). The sum of these components gives the final template continuous spectrum. The "burst" component responds to nebular emission line and nebular continuum radiation. For this reason, to rough fix the "burst" component parameters, we used the theoretical luminosity of [OII] forbidden emission line by fitting to the observed fluxes and taking into account the assumed reddening law. Here we used the observed [OII] fluxes from Bloom et al. (1998b) and Djorgovski et al. (1998), which are $(2.98 \pm 0.22) \cdot 10^{-17}\,{\rm erg\,s^{-1}\,cm^{-2}}$, and $(30.4 \pm 3) \cdot 10^{-17}\,{\rm erg\,s^{-1}\,cm^{-2}}$ for the host galaxies of GRB 970508 and GRB 980703, respectively. In addition, we estimated the contribution of the emission lines (not only [OII]) of the spectra of the host galaxies of GRB 970508 and GRB 980703 to broad-band magnitudes and found that it is negligible for our BVR_cI_c errors. Since PEGASE computes luminosity of emission lines separately from spectrum of star population and does not compute profiles of emission lines, in all Figures, with results of the modeling the profiles of emission lines will not be plotted. In the modeling we apply redenning only to the "burst" component, since extinction in a star-forming region is higher than over galaxy disk. Moreover, we used the local template, as a first approximation to get range of A_V, for which the extinction was obtained from ratio of emission lines, which in turn are associated with star-forming regions.

4.2. The host galaxy of GRB 970508

As was shown in Sect. 3, the BVR_cI_c broad-band flux spectrum is well approximated by the S5 template SED. According to $E(B-V) = 0.51 - 0.6$ we derived $A_V = 2.07 - 2.43$ for the SB extinction curve (Calzetti et al., 2000) and $A_V = 1.58 - 1.86$ for the MW extinction curve (Cardelli et al., 1989).

First, we performed the modeling for the SB extinction law using both $Z_\odot$ and $0.1Z_\odot$ metallicities as well as instantaneous and exponential decreasing star formation scenarios. In Figs. 5 and 6 the results of the modeling are presented. To constrain our models, in these Figures the upper limit of HST/NICMOS H-band flux from Pian et al. (1998) is plotted. In Table 4 we summarized the parameters of the resulting theoretical template SEDs, which corresponded to minimum of χ^2. Table 4 by the first column indicates the scenario of star formation, in the second and third columns the age and mass of the old component are given, and in the fourth and fifth columns the same parameters of the burst component are presented. For the exponential decreasing star formation scenario we also present the values of τ, which is the time when the star formation rate decreases by a factor of e. The sixth column denotes the metallicity of the theoretical template, the seventh column contains the model value of the [OII]3727Å emission line flux. We present the minimal value of χ^2 in the eighth column and in the last column the best fit values of extinction A_V are given.

Following our method we performed the theoretical modeling using also MW extiction law (Cardelli et al., 1989). We again assumed both metallicities and both star formation scenarios. The results of the modeling are presented in Figs. 7 and 8. The parameters of the model SEDs with minimal χ^2 are given in Table 5. The organization of Table 5 is the same as that

Table 4: *The parameters of the theoretical template SEDs corresponding to minimum of χ^2 for the host galaxy of GRB 970508 assuming Calzetti et al. extinction law**

Scenario	Old component Age, Gyr	Mass, $M_\odot$	Burst component Age, Myr	Mass, $M_\odot$	Metallicity	[OII] model flux**	χ^2_{min}/d.o.f.	A_V
Instantaneous	0.14	$3.16 \cdot 10^9$	1	$5.62 \cdot 10^7$	$Z_\odot$	$2.98 \cdot 10^{-17}$	0.66/4	2.07
burst	0.08	$1.00 \cdot 10^8$	4	$1.78 \cdot 10^8$	$0.1Z_\odot$	$2.92 \cdot 10^{-17}$	0.71/4	2.43
Exponential	1.2 ($\tau = 500$Myr)	$1.00 \cdot 10^9$	3 ($\tau = 300$Myr)	$5.62 \cdot 10^9$	$Z_\odot$	$2.61 \cdot 10^{-17}$	0.61/4	2.27
decreasing	0 ($\tau = 400$Myr)	$1.00 \cdot 10^9$	80 ($\tau = 400$Myr)	$5.62 \cdot 10^9$	$0.1Z_\odot$	$2.96 \cdot 10^{-17}$	0.68/4	2.17

* The parameters were obtained by fitting to BVR_cI_c data with the observed flux of [OII] emission line.

** The flux of the [OII] emission line derived in modeling (in units of $\mathrm{erg\,s^{-1}\,cm^{-2}}$).

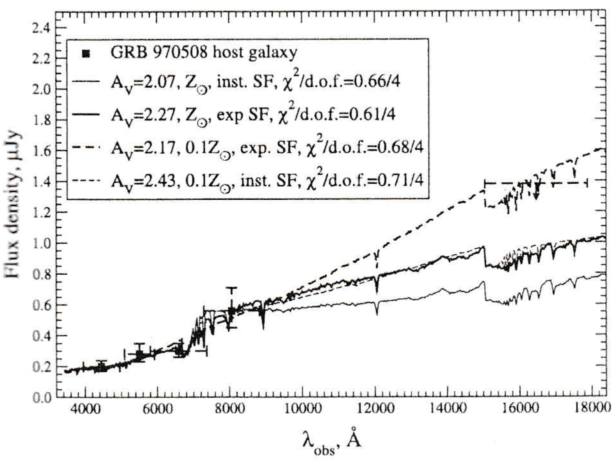

Figure 5: *The best fit for the model SED to BVR_cI_c broad-band flux spectrum of the host galaxy of GRB 970508 assuming the SB extinction law. Also the upper limit of HST/NICMOS H-band (Pian et al., 1998) is plotted. The observed wavelengths are given.*

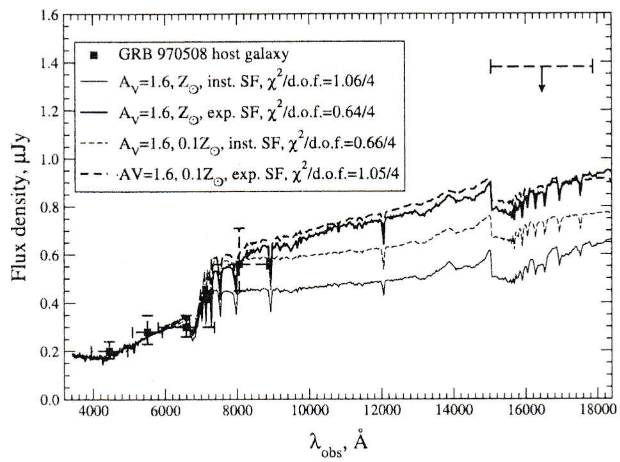

Figure 7: *The best fit for the model SED to BVR_cI_c broad-band flux spectrum of the host galaxy of GRB 970508 assuming the MW extinction law. Also the upper limit of HST/NICMOS H-band (Pian et al., 1998) is plotted. The observed wavelengths are given.*

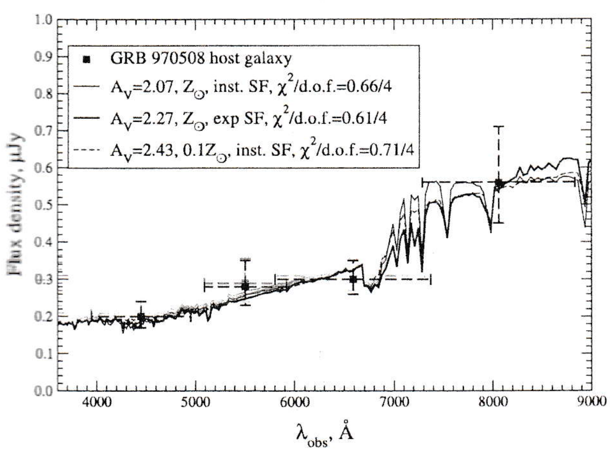

Figure 6: *The best fit for the model SED to BVR_cI_c broad-band flux spectrum of the host galaxy of GRB 970508 assuming the SB extinction law. The observed wavelengths are given.*

of Table 4.

It is important to note that we checked the values of χ^2 out of the range of A_V given by fitting to S5-template and found that the best fit theoretical templates correspond to the values of A_V, which lie in the S5-range. The results of the modeling imply that there is some uncertainty in the choice of the reddening laws. At least, as can be seen from Fig. 4, we may say that only one theoretical template with a metallicity of $0.1Z_\odot$ and exponential decreasing scenario for SB reddening law is not consistent with the upper limit of the H-band and, thus, can be ruled out. It is worth to note that in Tables 4 and 5 there are the models with the zero age of the "old" or "burst" component. This zero age means that the corresponding component is at the beginning of its time evolution and, therefore has a zero age. A more detailed analysis of the results of the modeling is given in Sect. 5.

Table 5: *The parameters of the theoretical template SEDs corresponding to minimum of χ^2 for the host galaxy of GRB 970508 assuming Cardelli et al. extinction law*

Scenario	Old component		Burst component		Metallicity	[OII] model	χ^2_{min}/d.o.f.	A_V
	Age, Gyr	Mass, $M_\odot$	Age, Myr	Mass, $M_\odot$		flux*		
Instantaneous	0.08	$1.78 \cdot 10^8$	0	$3.16 \cdot 10^7$	$Z_\odot$	$3.01 \cdot 10^{-17}$	1.06/4	1.6
burst	0.16	$3.16 \cdot 10^8$	0	$3.16 \cdot 10^7$	$0.1Z_\odot$	$3.00 \cdot 10^{-17}$	0.66/4	1.6
Exponential	1.0 ($\tau = 400$Myr)	$1.00 \cdot 10^9$	0 ($\tau = 10$Myr)	$3.16 \cdot 10^8$	$Z_\odot$	$3.01 \cdot 10^{-17}$	0.64/4	1.6
decreasing	1.2 ($\tau = 450$Myr)	$1.00 \cdot 10^9$	0 ($\tau = 10$Myr)	$3.16 \cdot 10^8$	$0.1Z_\odot$	$3.00 \cdot 10^{-17}$	1.05/4	1.6

* The flux of the [OII] emission line derived in modeling (in units of erg s^{-1} cm^{-2}).

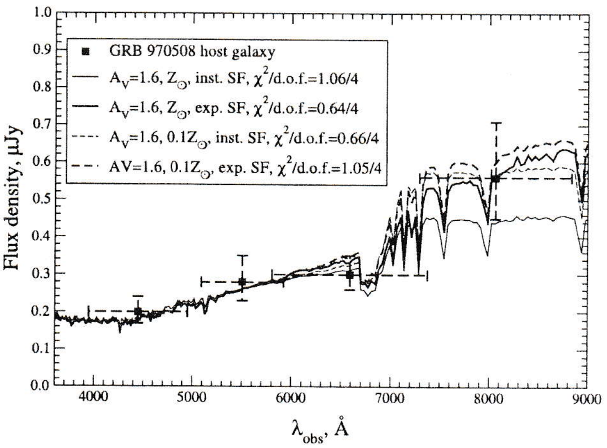

Figure 8: *The best fit for the model SED to BVR_cI_c broad-band flux spectrum of the host galaxy of GRB 970508 assuming the MW extinction law. The observed wavelengths are given.*

4.3. The host galaxy of GRB 980703

First, we should note that photometry of the host galaxy was performed about 20 days after the gamma-ray burst and it should be expected that there is an optical transient contribution. However, as was shown by Bloom et al. (1998a) the so-called flattening of the optical transient light curves is clearly seen less than 20 days after the gamma-ray burst. This flattening is due to the host galaxy light, which dominates in integral brightness of the optical counterpart. Thus we can suppose that the magnitudes from Table 1 are ones of the host galaxy.

As we reported above, the host galaxy is an S2 average local starburst with $E(B-V) = 0.11 - 0.21$ mag. According to the $E(B-V)$ we have computed $A_V = 0.45 - 0.85$ mag for the SB (Calzetti et al., 2000) reddening law and $A_V = 0.34 - 0.65$ mag for the MW (Cardelli et al., 1989) one, which is in agreement with the value of 0.3±0.3 mag obtained by Djorgovski et al. (1998) from the ratios of the Balmer lines. In the case of the host galaxy of GRB 980703 there are available JHK data. The observations were carried out with the NIRC instrument at the Keck 10 m telescope on 7 Aug. 1998 (Bloom et al., 1998a), e.g., later than our BVR_cI_c observations. Thus, we may assume that these JHK magnitudes are magnitudes of the host galaxy with a negligible contribution of the optical transient. To transform the magnitudes to the fluxes we used zero-points from Bessel & Brett (1998).

First, we performed the theoretical modeling assuming the SB extinction law and using both metallicities and star formation scenarios. The modeling shows that the theoretical templates do not well approximate the BVR_cI_cJHK broad-band flux spectrum in the UV domain (in the rest-frame).

The results of the modeling assuming the MW extinction law are presented in Figs. 9, 10 and the parameters of the templates are given in Table 6.

As well as in the case of the host galaxy of GRB 970508, we performed modeling out of the A_V range of the S2 templates and found that a minimum of χ^2 again lies within this range.

It is important to note that in the case of the host galaxy of GRB 980703 we have an opportunity to choose the internal extinction law using the observational data. Indeed, as can be seen in Fig. 10, there is some absorption feature at the B-band. This feature is related to the bump on the MW extinction curve (see Fig. 4). Using the obtained value of absorption we can estimate the flux deficit in the B-band in comparison to the I-band as if it was a continuous reddening law like Calzetti et al. (SB). This B-band flux deficit is equal to 40% 50% for $A_V = 0.51 - 0.64$ mag, which is really observed for our BVR_cI_c broad-band flux spectrum (see Fig. 10).

It would be useful to demostrate importance of the infrared data for the modeling. In Fig. 11 we demostrate a comparison of the theoretical templates obtained by fitting to BVR_cI_cJHK data and only BVR_cI_c data. Here we assumed the instantaneous burst of star formation, the Sun metallicity and the MW (Cardelli et al., 1989) extinction law. In the case of the fitting to the only BVR_cI_c data we obtained the best fit parameters as follows: for the "burst" component of the model the age is 3.0 Myr and the mass is $1.78 \cdot 10^8$ $M_\odot$; and for the "old" component (for the old stellar population) the age is 2.5 Gyr and the mass is $1.78 \cdot 10^{10}$ $M_\odot$. The parameters in the case of the fitting to the BVR_cI_cJHK data are given in

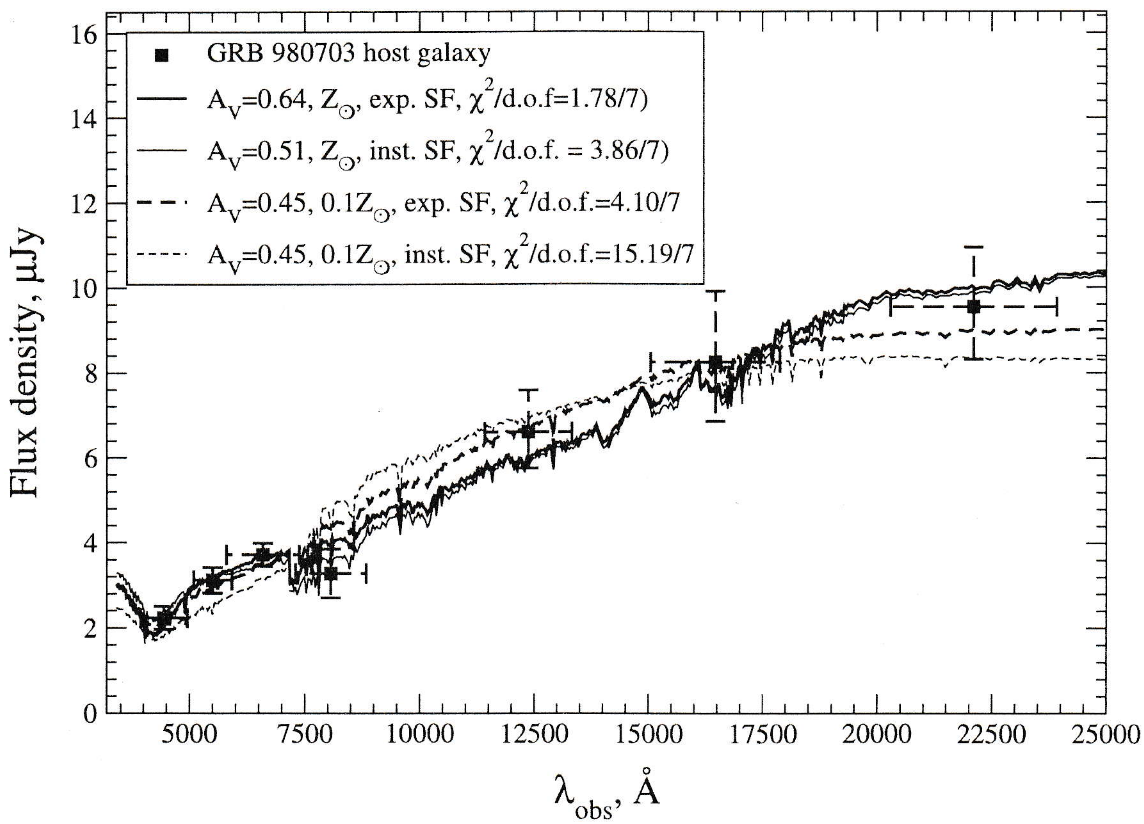

Figure 9: *The set of the model template SEDs for the host galaxy of GRB 980703 assuming the MW extinction law. The JHK data are taken from Bloom et al. (1998a) The observed wavelengths are given.*

Table 6: *The parameters of the theoretical template SEDs corresponding to minimum of χ^2 for the host galaxy of GRB 980703**

Scenario	Old component Age, Gyr	Mass, $M_\odot$	Burst component Age, Myr	Mass, $M_\odot$	Metallicity	[OII] model flux**	$\chi^2_{\min}$/d.o.f.	A_V
Instantaneous	3	$3.16 \cdot 10^{10}$	3	$1.78 \cdot 10^{8}$	$Z_\odot$	$27.8 \cdot 10^{-17}$	3.86/7	0.51
burst	1.8	$1.78 \cdot 10^{10}$	4	$1.78 \cdot 10^{8}$	$0.1Z_\odot$	$27.4 \cdot 10^{-17}$	15.19/7	0.45
Exponential	6 (τ = 350Myr)	$3.16 \cdot 10^{10}$	16 (τ = 150Myr)	$5.62 \cdot 10^{9}$	$Z_\odot$	$30.7 \cdot 10^{-17}$	1.78/7	0.64
decreasing	13 (τ = 50Myr)	$3.16 \cdot 10^{10}$	40 (τ = 500Myr)	$1.00 \cdot 10^{10}$	$0.1Z_\odot$	$31.5 \cdot 10^{-17}$	4.10/7	0.45

*The parameters were obtained by fitting to BVR_cI_cJHK data with the observed flux of [OII] emission line, which is $(30.4 \pm 3) \cdot 10^{-17}$ erg s^{-1} cm^{-2} (see text). ** The flux of the [OII] emission line derived in modeling (in units of erg s^{-1} cm^{-2}).

Table 6 in the first line.

As can be seen for the comparison, the fitting to the only BVR_cI_c data gives a lower flux in the near-infrared domain, but very close to the fitting to BVR_cI_cJHK data in the optics; and the parameters of the "burst" component are the same in the both cases, while the "old" component parameters are different. This can be explained as folows: the JHK bands ($\lambda_{\rm eff} = 12370, 16464, 22105$ ÅÅ, respectively) correspond to the optical window and near-infrared in the rest-frame (for $z = 0.835$, $\lambda_{\rm eff}/(1+z) = 6741, 8972, 12046$ ÅÅ for JHK, respectively), where the old stellar population dominates and the contribution of the "burst" component (or young stellar population) is small. The maximum of the burst contribution lies in the UV part of the spectrum which corresponds to the observed BVR_cI_c bands.

5. Discussion

We fulfilled the modeling of SEDs for the galaxies from Table 1 with the highest and the lowest luminosity: the host galaxy of GRB 970508 and GRB 980703. As was described in Sect. 4, we achieved this goal using two approximations. First, the range of A_V was derived using comparison of the BVR_cI_c broad-band

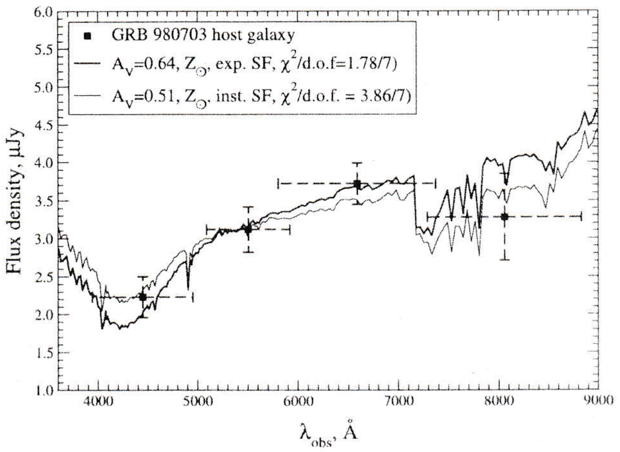

Figure 10: *The SED model fitting of BVR_cI_cJHK broad-band flux spectra as well as in Fig. 9, but shown only BVR_cI_c part of the spectra.*

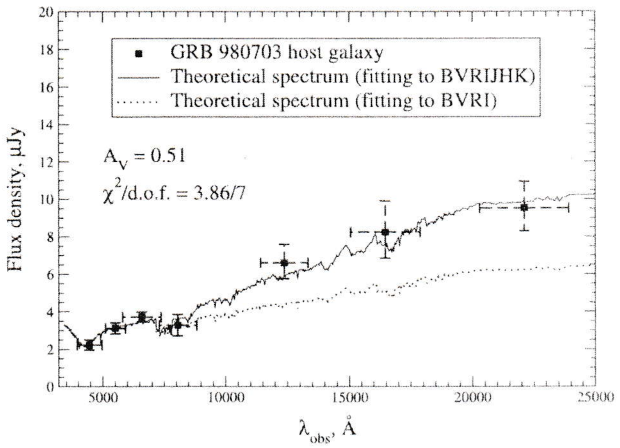

Figure 11: *Comparison of the theoretical templates obtained by the fitting to BVR_cI_cJHK data (solid line) and the only BVR_cI_c data (dotted line). The instantaneous burst of star formation, the Sun metallicity and the MW extinction law were assumed. The observed wavelengths are given.*

flux spectra with local starburst templates. The second approximation is the theoretical modeling (or computing the theoretical templates), which allows us to choose the reddening law and the certain value of A_V. The selected model parameters for these two GRB host galaxies are presented in Table 7. Let us discuss the results of the modeling.

The host galaxy of GRB 970508: As was noted in Sect. 4.2, in the case of the host galaxy of GRB 970508, there is some uncertainty in the choice of the reddening law. As the first approximation we derived the range of A_V for both reddening laws, A_V= 2.07 − 2.43 mag and A_V= 1.58 − 1.86 mag for Calzetti et al. and Cardelli et al. extinction laws, respectively. The modeling was performed in these ranges and the minimum of χ^2 actually occurs within both of them. We found that for the Cardelli et al. extinction law the value of A_V does not depend on the star formation scenario and metallicity, while for Calzetti's law this dependency is clearly seen. As can be seen from Tables 5 and 7, in some cases the minimal value of χ^2 takes place for models with burst component masses of the same order of the old component mass or even higher. This is unlikely to be real. It is clear that a rather large amount of gas in the galaxy is needed to initiate formation of such a massive population. As it follows from the tables this mass of gas is to exceed the total mass of galaxy or to be at least of the same order, which seems to be unbelievable. On the other hand, this situation is likely to happen in the case of primeval galaxies, i.e. the galaxies where the first burst of star formation occurs. Nevertheless, the observations do not confirm the formation of primeval galaxies at z=0.835, in any case. Thus, the model of the instantaneous burst scenario and a metallicity of $Z_\odot$ for the Calzetti et al. extinction law and the same scenario with both metallicities in the case of the Cardelli et al. extinction law seems to be more reasonable. Should one come back to the ages of the old component, it can be noticed that the theoretical template SEDs correspond to young galaxies, which in turn leads to the conclusion about a lower metallicity in comparison with that of the Sun. It follows from these considerations that SED from Table 5 with the following parameters: instantaneous burst of star formation, metallicity of $0.1Z_\odot$ and A_V= 1.6 mag for the Cardelli et al. (MW) extinction law, is the most appropriate model. The selected parameters of the host galaxy are given in Table 7.

As was found by Fruchter et al. (2000) the host galaxy of GRB 970508 is best fitted by a model disk with an exponential distribution of surface brightness. The scale length r_0 after correcting for the HST/STIS PSF was measured to be 0.046 ± 0.006. Using a simple relation between the central surface brightness μ_0, the 25 mag/arcsec^2 isophotal angular radius r_{25} (in arcsec), and the scale length r_0:

$$25 - \mu_0 = \frac{r_{25}}{r_0} 2.5 \log(e),$$

we can estimate μ_0. As can be estimated from Frucher et al. (2000) (Fig. 2) the r_{25} is about $0.''25$. Then μ_0 would be about 19.1 mag/arcsec^2 (HST/STIS open filter mode photometric system). Following Sokolov et al. (1999), we can obtain the position of the host galaxy of GRB 970508 on the diagram M_B vs. linear diameter $\log D_{25}$. Assuming cosmology from Sect. 3 we obtained M_B and $\log D_{25}$ to be −18.6 and 0.65 [kpc], respectively. This is within the marked regions previously found by Sokolov et al. (1999, see

Table 7: *The selected parameters of two host galaxies*

Host	Scenario	Metallicity	Total mass	Age	A_V	Observed SFR*	Corrected SFR
GRB 970508	instant. burst	$0.1Z_{\odot}$	$3.48 \cdot 10^8$	160 Myr	1.6	$\geq 1.4\,M_{\odot}\,yr^{-1}$	$14\,M_{\odot}\,yr^{-1}$
GRB 980703	exp. decreasing	$Z_{\odot}$	$3.72 \cdot 10^{10}$	6 Gyr	0.64	$\geq 10\,M_{\odot}\,yr^{-1}$	$20\,M_{\odot}\,yr^{-1}$

* The SFR was recomputed following cosmology with H_0=60 km·s^{-1}·Mpc^{-1}, Ω_M=0.3 and Ω_Λ=0.7.

their Fig. 6) from preliminary results of Fruchter et al. (1998). Thus, the analysis of the surface brightness distribution gives surface brightness higher than normal (as it should be for Mrk galaxies), which suggests a starburst activity. However it should be noted that the surface brightness analysis was performed for object with size of one order of STIS/HST PSF and there is an uncertainty in exact estimation of the central surface brightness of the host galaxy. Nevertheless, as was shown from the high ratio of the fluxes of the emission lines [NeIII]/[OII]= 0.44 ± 0.05 (Bloom et al., 1998b), one can suggests that there is a population of massive and hot stars (see Bloom et al., 1998b). So, high ratio of the emission lines also may be interpreted as an existence of an AGN. But, no one GRB host galaxy or GRB OTs spectrum shows any evidence for high-ionization lines such as Mg II λ2799, [NeV]λ3346 and [NeV]λ3426 as would be expected in an AGN. Combining all we can conclude that the host galaxy of GRB 970508 is an actively star-forming young galaxy, which is in agreement with the results of the modeling. Our value of the intrinsic extinction allows us to derive the corrected SFR. Using the Cardelli et al. (MW) reddening curve and A_V mag, we computed that the SFR should be corrected by a factor of about 10. The lower limit of the SFR from the luminosity of the [OII] emission line derived by Bloom et al. (1998b) is about $1\,M_{\odot}\,yr^{-1}$, the extinction corrected SFR will then be about $10\,M_{\odot}\,yr^{-1}$ for the cosmological parameters assumed by Bloom et al. (1998b).

The host galaxy of GRB 980703: As was shown in Sect. 4.3, in the case of the host galaxy of GRB 980703, the observational data make it possible to choose the only extinction law similar to that in the Milky Way (Cardelli et al., 1989). Thus, in the second approximation we investigated only one range of A_V= 0.3 – 0.65 mag, which corresponds to the Cardelli et al. extinction law. As can be seen from Fig. 9, the theoretical templates with a metallicity of $0.1Z_{\odot}$ systematically deviate from the observed BVR_cI_cJHK broad-band fluxes, particularly in the BVR_cI_c and K-band domain. The fact that the BVR_cI_cJHK data are best described by the models with solar metallicity is naturally explained by the age of the old component of the stellar population. Indeed, the time of order of 6 Gyr is enough to enrich the medium with heavy elements. Moreover, existence of the graphite feature at 2800Å (in the rest-frame, see Figs. 4 and 10) again is in consistency with the solar metallicity. The final parameters of the host galaxy are given in Table 7.

As in the case of the host galaxy of GRB 970508, if the internal extinction is known, we can estimate the SFR corrected for the latter. As was found by Djorgovski et al. (1998), the lower limit to the SFR for the GRB 980703 host is about $7\,M_{\odot}\,yr^{-1}$, which was derived from the H_β luminosity. Then, using the Cardelli et al. (1989) reddening law and A_V= 0.64 mag, we derive the SFR to be $\sim 14\,M_{\odot}\,yr^{-1}$ for the cosmology assumed in Djorgovski et al. (1998). But it should be noted that the recent radio data show a significantly higher value of the SFR. As was found by Berger et al. (2001) the total SFR is about $500\,M_{\odot}\,yr^{-1}$. In order to reconcile the optical and radio derived SFRs, one should require a rest-frame extinction of about $A_V\sim$ 4.5 mag (Berger et al., 2001), that is more higher than was obtained by us. Probably, this is due to difference of the extinction over the galaxy. The nuclear star-forming region, from which the radio emission goes, has a more higher extinction than the average over the whole galaxy. The size of the radio-emitting region is very small (upper limit of the radio diameter is $D_{\rm rad} < 2.3$ kpc, whereas optical size of the galaxy is $D_{\rm opt} \approx 3.7$ kpc) and ground-based observations can not resolve it. Because of this, we measure the extinction averaged over the optical image of the galaxy and regions with more higher extinction do not show any features in the spectrum. But so high values of SFR can be obtained not only from radio observations. As was found by Sokolov et al. (2001) from the emission lines of the optical transient spectrum of GRB 991208 the extinction corrected SFR was obtained to be $100 - 200\,M_{\odot}\,yr^{-1}$ or even higher. In the case of the host galaxy of GRB 990712, again from the optical emission line spectrum, the extinction corrected SFR was found to be high, about $60\,M_{\odot}\,yr^{-1}$ (Vreeswijk et al., 2001). As was performed for the host galaxy of GRB 970508 there are results of the surface brightness analysis of the host galaxy of GRB 980703. As was found by Holland et al. (2001) from the analysis of the HST/STIS data, the host galaxy is best fitted by a Sersic $R^{1/n}$ profile with $n \approx 1.0$. This corresponds to an exponential disk with a scale radius of $0''.22$ ($1.21h_{100}^{-1}$ proper kpc) and $<\mu_c>=\mu_0 \approx 20.4$ mag. Subtraction of a fit with elliptical isophotes showed that morphology of the host galaxy is somewhat irregular. From the analysis Holland et al. (2001) concluded that the host galaxy of GRB 980703 is a typical example of a compact star-forming galaxy similar to those found in the Hubble Deep Field.

To discuss the method of the modeling one can note that scenarios of the star formation we chose seem to be simple. Real scenarios might be more complex. For instance, Glazebrook et al. (1999) showed from the analysis of ratio UV flux to H_α emission line that the star formation history can have a repeating form. Because of this we can underestimate ages of the old stellar population and consequently probably mass of this population. In addition, there is some uncertainty in IMF (initial mass function). The precise form of stellar IMF in starburst galaxies is open to question. It is very important to know high-mass cut-off of the IMF. It is obvious that UV part of the spectrum, where we perform our modeling, strongly depends on the exact value of high-mass cut-off. As was shown in Sect. 4.3, for modeling it is quite sufficient to know infrared data for more exact fit of the old stellar population contribution in resulting theoretical SED.

Anyway, one of the interesting consequences of our modeling is related to the problem of so-called dark GRBs. From about 30 GRBs with X-ray afterglows detected by the WFC of BeppoSAX $60 \pm 15\%$ had no optical afterglow, and this is due to neither adverse observing conditions nor delay in performing the observations (Lazzati et al., 2001; see also Fynbo et al., 2001). As was discussed by Ramirez-Ruiz et al. (2001), the cases of no detection of optical afterglow can be explained by two moded of star-formation. The first mode is star formation in galaxies that are bright at rest-frame submillimetre (submm) and infrared wavelengths, and the second is star formation in galaxies, which show strong UV continuum. The first is related to high internal extinction (towards the central power sources in Arp 220, $A_{\rm V}$ is greater than ≈ 30 mag) and thus re-emission of the UV flux to the far infrared and submillimetre domain. High-redshift submm selected galaxies are thought to have properties similar to those of the local ultraluminous infrared galaxies (ULIGs) like Arp 220. Because of the high internal extinction, optical afterglow can be obscured by surrounding medium and we will have no detection. We showed that the internal extinction in GRB host galaxies is not so high ($A_{\rm V}\sim 2$ mag - in our modeling, $A_{\rm V}\sim 3$ - as was found by Vreeswijk et al., 2001). All the discussed GRB host galaxies have an UV continuum (see Sect. 3) and no one shows strong UV obscuration. Perhaps, GRB host galaxies, where optical transient was detected, are ones with the second mode of star formation. A very interesting result was obtained by the radio observations of the host galaxy of GRB 980703. Using correlation between the radio and far infrared luminosities of star-forming galaxies, Berger et al. (2001) found that $L_{\rm FIR} \approx 3 \times 10^{12}\, L_\odot$, that places the host galaxy of GRB 980703 in category of ULIGs at the faint end of their luminosity function. It seems that this host galaxy is a transitional kind of galaxies between UV-bright and ULIG galaxies.

In the following, we compare $\mathrm{M_{B_{rest}}}$ from Table 1 with the local value of M_*. We assumed the local M_* to be -21 mag. As can be seen the luminosities of the hosts are certainly not above the "knee" of the local luminosity function (excluding the host galaxy of GRB 000926). We have shown that in GRB host galaxies there may be a significant internal extinction and, thus, perhaps the observational fact that GRB host galaxies are underluminous is due to obscuring of the UV and optical flux by dust and/or dense molecular clouds.

However, it is clear that more correct comparison can be performed if we have a value of M_* as a function of redshift. Thus, in addition, we compared our $\mathrm{M_{B_{rest}}}$ magnitudes from Table 1 with the recent results of Fried et al. (2001). These authors present the results from the CADIS survey which include a study of the luminosity function of various types of galaxies as a function of redshift (in particular their Table 2). They present the data for an $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\Lambda = 0.7$ and $\Omega_{\rm M} = 0.3$ cosmological model. To transform the M^* magnitudes from Table 2 of Fried et al. (2001) to our cosmology (with $H_0 = 60\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$), we used the relation $M_{60} = M_{100} - 1.1$. Then the M^* magnitudes are increased to be $M^* \approx -20.1 \pm 0.2$ mag in the redshift range of $0.3 - 0.5$, $M^* \approx -21.5 \pm 0.3$ mag in the redshift range of $0.5 - 0.75$ and $M^* \approx -21.0 \pm 0.2$ mag in the redshift range of $0.75 - 1.04$ for starburst galaxies from Table 2 by Fried et al. (2001). The comparison with the absolute magnitudes from our Table 1 shows that the $\mathrm{M_{B_{rest}}}$ of the host galaxies of GRB 990712, GRB 980613 and GRB 980703 corresponds to M^* from Fried et al. (2001). The $\mathrm{M_{B_{rest}}}$ of the host galaxy of GRB 000926 is higher than M^* of Fried et al. (2001), but the estimates of the $\mathrm{M_{B_{rest}}}$ was derived by scaling the local templates and may be uncertain. The $\mathrm{M_{B_{rest}}}$ of the hosts of GRB 970228, GRB 970508 and GRB 991208 are much lower than the M^*, but we pay attention to the fact that the observed I-band magnitudes of these hosts are fainter by 1 mag than the completeness limit of the CADIS survey ($I_{815} = 23.0$, Fried et al., 2001). The redshifts of the other five hosts from our Table 1 are out of the redshift range of the CADIS survey.

In the end we can say: it seems that GRB host galaxies do not differ from galaxies at the same redshift. Indeed, the comparison of the absolute mag-

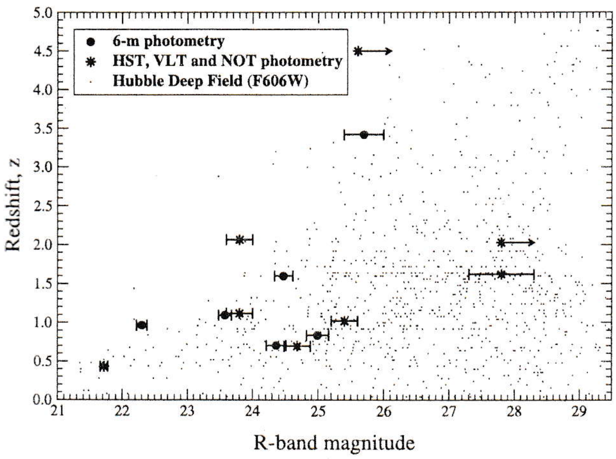

Figure 12: *Observed R-band vs. redshift diagram of 14 GRB host galaxies. Also the HDF F606W magnitude vs. photometrical redshift distribution is plotted. The catalogue of the F606W magnitude and photometrical redshift was used from Fernández-Soto et al., 1999.*

nitude with the results of the CADIS survey shows that $M_{B_{rest}}$ is close to the "knee" of the CADIS luminosity function. Moreover, as was shown by Glazebrook et al. (1999), the mean star formation rate of z=1 (median redshift of GRB host galaxies) is $\sim 20 - 60\,M_{\odot}\,yr^{-1}$ that is similar to the estimates of the SFR for GRB host galaxies. In Fig. 12 we present the *R*-band magnitude vs. redshift diagram for 14 GRB host galaxies in comparison with the results of photometrical redshift procedure applied to the Hubble Deep Field (Fernández et al., 1999). As can be seen, the distribution of GRB host galaxies does not differ from that of the field galaxies.

6. Conclusion

To summarize the results of the modeling, we can conclude the following.

(i) Broad-band flux spectra of GRB host galaxies are well fitted by SEDs of the local starburst galaxies.

(ii) UV part of GRB host galaxy SEDs is properly described by theoretical models with young burst of star formation. Moreover for $z \sim 1$ in the optical waveband, in fact, we observe **only star-forming regions** in GRB host galaxies, because they dominate in the rest-frame UV part of the spectrum.

(iii) It is important to take into account the effects of the internal extinction in modeling of GRB host galaxy SEDs.

iv) GRB host galaxies seem to be the same as galaxies at the same redshift.

Acknowledgements. The work was supported by the "Astronomy" Foundation (grant 97/1.2.6.4) and RFBR N01-02-17106a

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