Decay of the GRB 990123 Optical Afterglow: Implications for the Fireball Model

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ABSTRACT

Multiwavelength, photometric measurements appear as a useful tool, for the understanding of cosmic γ-ray bursts. Proper modelling would give insight into the expanding fireball, and possibly also to the underlying energy source. Our broad-band (ultraviolet to near-infrared) observations of the exceptionally intense γ-ray burst, GRB 990123, started $\sim$ 8.5 hours after the event and have continued until 18 Feb 1999. When combined with data from elsewhere, in particular from the Robotic Telescope and Transient Source Experiment (ROTSE) and the Hubble Space Telescope (HST), evidence emerges for a smoothly declining light curve, suggesting some color dependence, that could be related to a cooling break passing the UV-optical band at about 1 d after the high energy event. We also interpret a steepening decline rate seen after 1.5-2 d as evidence for a collimated jet pointing towards the observer.

Gamma–ray bursts (GRBs) are brief flashes of cosmic high energy ($\sim$ 10 keV–10 GeV) photons. They have remained without any satisfactory explanation since discovery in 1973 (*1*). With the advent of the Italian–Dutch x–ray satellite BeppoSAX, it became possible to conduct deep counterpart searches only a few hours after a burst. This led to the first detection of X-ray and optical afterglow, for GRB 970228 (*2*). Subsequent observations have shown that about half of the well localized GRBs can be associated with optical emission, that gradually fades fades away, over weeks to months (*3*). About 10 such cases are now known. Models proposed already before the first detection of optical afterglow (*4*) have been remarkably successful in describing the decline of the optical emission. The afterglow is explained as due to synchrotron radiation from relativistically expanding matter, colliding internally, or with the interstellar medium.

GRB 990123 was detected on 23 Jan 1999, UT 09:47 by the GRB monitor and the wide-field camera (WFC) of BeppoSAX, and by three instruments on board the Compton Gamma–ray Observatory, the Burst and Transient Source Experiment (BATSE), the Compton Telescope (COMPTEL) and the Oriented Scintillation Spectrometer Experiment (OSSE). A complex light curve was obtained, lasting $\sim$ 100 s (*5*). The γ-ray fluence was $\sim 5.1 \times 10^{-7}$ J m^{-2} (*6*). This places the burst in the top 0.3 % of the BATSE GRB fluence distribution and it is one of the brightest events within the COMPTEL and OSSE range ($>$ 0.7 MeV) (*7*).

After 6.0 h, BeppoSAX was reoriented towards the burst location, and a previously unknown x–ray source was detected (*8*). The source intensity 1.6 ($\pm$ 0.2) $\times\ 10^{-14}$ J m^{-2} s^{-1} (2–10 keV), makes this x-ray afterglow the brightest detected so far. Optical observation conducted in response to the BeppoSAX localization led to the identification of an Optical Transient (OT) (*9*), associated with the GRB: this OT was initially seen as an object of a red broad-band magnitude R =

18.2 (*10*). Optical observations had, however, begun much earlier. In response to the internet-transmitted trigger from BATSE, ROTSE at Los Alamos National Laboratories (*11*) had started wide-angle imaging already 22 seconds after the beginning of the GRB. Off-line analysis, conducted after the above-mentioned identification, revealed that the OT had been detected already in the first exposure, and had peaked at visual broad-band magnitude V $\sim$ 9, some seconds later.

Optical spectroscopic observations revealed that the redshift of the burst source is $1.6 \leq z < 2.0$ (*12, 13*). Assuming isotropic emission, a Hubble constant of H_0 = 70 km s^{-1} Mpc^{-1}, and a cosmological density parameter $\Omega_0 = 0.3$, this implies an energy release in γ-rays alone of $\sim 2.5 \times 10^{54}$ erg, using the BeppoSAX GBM data. This is significantly larger (by a factor of 10-100) than measured for any of the four other GRBs for which a redshift is known.

We have obtained optical and near-IR images centered on the GRB location starting 8.5 h after the burst (Table 1). For the optical images, photometry was performed by means of SExtractor (*14*), making use of the corrected isophotal magnitude, which is very appropriate for star-like objects. As the OT was generally quite faint on the later epoch images, the DAOPHOT (*15*) profile-fitting technique was used for the magnitude determination. Zeropoints, atmospheric extinction and color terms were computed using observations of standard fields taken throughout the run. Magnitudes of the secondary standards in the GRB fields agree, within the uncertainties, with those given by Nilakshi *et al.* (*16*). Zeropoint uncertainties are also included in the given errors. For the IR images, the JK-band calibration is based on the calibration performed by Guetter *et al.* (*17*) who observed a nearby star under photometric conditions just before observing the GRB 990123 field.

A comparison among optical images acquired on 23 and 24 Jan allowed us to confirm the variability in intensity of the proposed OT (*10*). When compared to stars in the field, the object shows an ultraviolet (UV) excess, further supporting the association of the transient x-ray source with the OT. About 8.5 h after the burst, we measured R = 19.10 $\pm$ 0.15 for the OT, and 19 h later we found R = 19.99 $\pm$ 0.07 and a broad-band ultraviolet magnitude of U = 19.92 $\pm$ 0.03. In these images the object is point-like (resolution $\sim 1''$) and there is no evidence of any underlying extended object as seen at later epochs (Fig. 1).

Our first optical observation was done nearly simultaneous to the BeppoSAX narrow-field instruments (NFI) observation, which began 6 h after the burst, implying a ratio of x–ray (2-10 keV) to optical luminosity (R-band) ~ 10, similar to GRB 970508 (*18*) but in contrast to ~ 200 for GRB 970228 (*19*).

Our UBVRI light curve (Fig. 2) shows that the source was declining in brightness. To obtain the flux due to the OT we have excluded the contribution of the underlying galaxy that was detected with HST (*20*). For the galaxy alone we have considered our broad-band measurements of U = 23.60 $\pm$ 0.15 on 17.2 Feb, B = 24.23 $\pm$ 0.10 (blue) on 13.2 Feb and I = 23.65 $\pm$ 0.15 (near-infrared) on 18.2 Feb which, together with V = 24.20 $\pm$ 0.15 on 9.1 Feb (*20*) and R = 23.77 $\pm$ 0.10 on 14.5 Feb (*21*) imply a flat spectral distribution ($F_\nu \propto \nu^\beta$ with $\beta \sim 0$) as expected in the rest-frame UV for a star-forming galaxy (*22*).

A single power law decay, as predicted by the single afterglow models, with the flux $F \propto t^\delta$ where t is the time since the onset of the GRB, arbitrarily defined on the basis of the BATSE data, and δ is the power-law decay exponent, does not fit the data obtained beginning 3 h after the burst (as can be seen from the high χ^2/dof values in Table 2). We also included in the fit other observations given in the literature (*23*), brought to a common photometric system. The results are even worse if we consider the ROTSE data (*11*) and the magnitude derived from the HST observation on 9.1 Feb (*20*). This implies that a single power-law is not the best model.

The ROTSE and HST points can be transformed to the R-band magnitudes by assuming that V−R $\sim$ 0.3 (based on our earliest and latest observations). Then we find however that the overall R-band light curve, better sampled that the other bands, can be better fit when three distinct power-law decays are considered, especially during the time intervals 3 h $<$ t $<$ 2 d and 2 d $<$ t $<$ 20 d (Fig. 3 and Table 3). Therefore, for the rest of broad-band data and due to the lack of measurements after 2 d, we have performed fits only for the time interval 8 h $<$ t $<$ 2 d (see Table 4). The BVRI-band fits are much more acceptable that those given in Table 2. Although suggestive of a temporal decay rate gradual change, the multicolor fit is also consistent, within a 2.5σ uncertainty, with a single power-law with $< \delta > = -1.22 \pm 0.08$.

GRB optical afterglows can be generally explained in terms of the "standard" fireball model (*24*), under the assumption of an impulsive energy input characterized by a given energy and a bulk Lorentz factor. A forward relativistic blast wave is moving ahead of a fireball, and sweeps up the interstellar matter, decelerating with time, and producing an afterglow at frequencies gradually declining from x-rays to visible and radio wavelengths. The properties of the blast wave can be derived from the classical synchrotron spectrum (*25*) produced by a population of electrons with the addition of self absorption at low frequencies and a cooling break (*26*). The population of electrons has a power-law distribution of Lorentz factors γ_e following $\mathrm{d}N/\mathrm{d}\gamma_e \propto \gamma_e^{-p}$ (above a minimum Lorentz factor $\gamma_e \geq \gamma_m$ corresponding to the synchrotron frequency ν_m) where p is the usual index of the electron energy distribution.

According to the current view, the forward external shock would have led to the afterglow as observed in all wavelengths (*27*). On 24.2–26.2 Jan UT, the equivalent spectral slope β (with $F_\nu \propto \nu^\beta$) between the optical band and the x-rays is $\beta_{ox} = -0.68 \pm 0.05$ (Fig. 4), in agreement with the optical spectroscopy obtained on the same date (*13*), and similar to the spectral indexes of other x-ray afterglows in which $\beta_{ox} \simeq -0.5$ to -1.0 (*28*). Our nearly-simultaneous UBVRI observations and upper limits (Table 1) for the J and K band measurements on 24.2 Jan UT, imply R$-$J $\leq$ 1.6, R$-$K $\leq$ 2.8, and are in agreement with the above-mentioned values of β_{ox}, indicating a non-reddened spectrum.

The optical afterglow is fit by a single power-law up to $t \approx 1.5$–2 d. Thereafter, a different, steeper power law index is required to fit the data well. A possible explanation for the possible gradual change of δ between $\sim$ 8 h and 2 d in the UBVRI bands could be the passage of the cooling frequency across the UV-optical range at $\sim$ 1 d. Assuming an adiabatic blast wave and that the cooling break fequency ν_c was above the UV on 24.2 Jan, we can consider $F_\nu \propto \nu^{-0.7}$ (for $\nu < \nu_c$) as observed in our spectrum taken on 24.2 Jan (*12*). This implies a temporal decay $F_\nu \propto t^{-1.05}$ for $\nu < \nu_c$ and $F_\nu \propto t^{-1.3}$ for $\nu > \nu_c$, with a slow transition from one behaviour to the other ($\nu_c \propto \mathrm{t}^{-0.5}$). This transition could have been hinted in our measurements (Table 4).

With respect to the break seen after 1.5-2 d, a possibility will be the transition for spherical ejecta to a non-relativistic phase (*13*), but an alternative would be the existence of a strongly collimated jet pointing toward us that has begun to spread (*29*), although this cannot be definitively proven on the basis of the polarimetric measurements (*30*).

The observed power-law with δ = -1.75 $\pm$ 0.11 is also expected from seeing the edge of the jet (*31*), which occurs well before sideways expansion starts (*32*). The break due to a sideways expansion in the decelerating jet occurs when the initial Lorentz factor Γ drops below ${\theta_0}^{-1}$ (with θ_0 the initial opening angle). For the latter a change in δ from $3(1-p)/4$ to $-p$ (for $\nu_m < \nu < \nu_c$), or from $(2-3p)/4$ to $-p$ (for $\nu \geq \nu_c$) is expected. ¿From the x-ray (2-10 keV) data obtained after 6 h, δ_x = -1.44 $\pm$ 0.07 was derived (*33*), which implies p = 2.58 $\pm$ 0.10 for the fast cooling electrons. And from δ_R = -1.13 $\pm$ 0.02 in the R-band, we should get p = 2.50 $\pm$ 0.03 (2.17 $\pm$ 0.03) for the slow (fast) cooling electrons. Then we consider p = 2.50 $\pm$ 0.03 and consequently, the OT light curve may continue to steepen, ultimately approaching a slope $\delta \sim -2.5$.

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FIGURES AND TABLES

Fig. 1. Ultraviolet (U band) images of the OT 990123 location. The images were taken on 24 Jan, UT 04:35 (18.8 hr after the GRB, *left panel*), and on 17 Feb, UT 05:00 (24 d after the GRB, *right panel*). It shows the optical afterglow (arrow), and the underlying galaxy at the center of the image. The field is $2.1' \times 2.1'$. North is at top and east is to the left. Limiting magnitudes were U $\sim$ 22, and $\sim$ 24.5, respectively.

Fig. 2 The UBVRI-band light-curves of the optical transient related to GRB 990123, including the underlying galaxy. Filled circles are our data, and empty circles are data taken from the literature (*23*). The latter have been brought to a common photometric system. The dashed-line is the pure OT contribution to the total flux, according to the fits given on Table 4 for the period 3 h $<$ t $<$ 2 d. The solid line is the combined flux (OT plus underlying galaxy).

Fig. 3 The R-band light-curve of the GRB 990123 optical transient. Based on our observations and other data reported elsewhere (*11,23*). The diamond is the pure OT flux as derived from the HST observation (*20*). The dotted line is the contribution of the underlying galaxy, with R $\sim 23.77 \pm 0.10$, from (*21*). The three dashed lines are the contribution of the OT, following F $\propto t^{\delta}$ with $\delta = -2.12$ up to $\sim$ 10 min, $\delta = -1.13$ up to $\sim$ 1.5 d, and $\delta = -1.75$ after that time. The solid line, only drawn after 1.5 d for clarity is the total observed flux (OT + galaxy).

Fig. 4. The multiwavelength spectrum of GRB 990123 on 24–26 Jan 1999 UT. The two first x–ray data points (24.2 Jan and 25.2 Jan) are the BeppoSAX

NFI measurements obtained at that time. The third one is the extrapolation following the power-law decay seen in x–rays, from (*33*). Circles are the data obtained on 24.2 Jan UT, squares are the data obtained on 25.2 Jan UT, and diamonds are the data obtained on 26.2 Jan UT. The correction for galactic extinction has been considered taking into account E(B-V) = 0.016 from (*34*). A fit to the optical to x–ray spectral flux density is consistent on the three dates with $\beta = -0.68 \pm 0.05$.

Table 1. Journal of the GRB 990123 optical/IR observations

Date of 1999	Time (UT)	Telescope	Filter	Integration time (s)	Magnitude
23 Jan	18:09	0.6 BAO	R	1,200	19.10 ± 0.15
23 Jan	22:15	1.0 UPSO	R	1,200	19.42 ± 0.17
23 Jan	23:00	1.0 UPSO	R	2,400	19.69 ± 0.06
24 Jan	02:18	2.5 NOT	R	180	19.89 ± 0.04
24 Jan	02:23	2.5 NOT	R	180	19.88 ± 0.04
24 Jan	02:28	2.5 NOT	V	180	20.21 ± 0.06
24 Jan	02:33	2.5 NOT	V	180	20.18 ± 0.06
24 Jan	02:56	1.5 Loiano	I	1,200	19.66 ± 0.14
24 Jan	03:24	1.5 Loiano	R	1,500	19.99 ± 0.07
24 Jan	03:56	1.5 Loiano	V	1,800	20.32 ± 0.07
24 Jan	03:59	2.5 NOT	R	6 x 300	20.07 ± 0.02
24 Jan	04:26	2.5 NOT	B	300	20.68 ± 0.03
24 Jan	04:35	2.5 NOT	U	600	19.92 ± 0.03
24 Jan	04:39	1.5 Loiano	B	2,700	20.62 ± 0.08
24 Jan	05:11	1.5 Loiano	R	600	20.14 ± 0.10
24 Jan	06:20	0.8 IAC	R	900	≥ 19.5
24 Jan	06:36	0.8 IAC	I	900	≥ 19.0
24 Jan	11:56	4.0 KPNO	U	900	20.50 ± 0.10
24 Jan	19:07	0.6 BAO	R	3,600	20.84 ± 0.30
24 Jan	22:14	1.0 UPSO	R	3,600	20.83 ± 0.08
25 Jan	03:28	1.5 Loiano	R	2 x 1,500	21.14 ± 0.15
25 Jan	04:30	2.2 CAHA	R	2 x 300	≥ 21.0
25 Jan	04:52	1.5 Loiano	V	2 x 1,500	21.35 ± 0.18
25 Jan	06:25	2.5 NOT	U	2 x 600	21.11 ± 0.06
25 Jan	06:45	0.8 IAC	R	900	≥ 20.5
25 Jan	06:50	2.5 NOT	B	2 x 300	21.76 ± 0.05
25 Jan	07:01	0.8 IAC	I	667	≥ 19.5
25 Jan	07:01	2.5 NOT	V	2 x 180	21.52 ± 0.07
25 Jan	07:10	2.5 NOT	R	2 x 180	21.18 ± 0.11

25 Jan	07:17	2.5 NOT	I	180	20.85 ± 0.25
25 Jan	21:30	0.6 BAO	R	2,400	21.40 ± 0.25
25 Jan	22:33	1.0 UPSO	R	2,400	21.34 ± 0.15
25 Jan	23:45	1.0 UPSO	V	3,600	21.89 ± 0.20
26 Jan	03:19	1.5 Loiano	R	3 x 1,500	21.90 ± 0.20
26 Jan	03:46	1.5 Loiano	V	2 x 1,800	22.33 ± 0.17
26 Jan	03:55	3.5 CAHA	I	900	21.75 ± 0.30
26 Jan	04:23	3.5 CAHA	R	900	21.87 ± 0.10
26 Jan	04:41	3.5 CAHA	B	900	22.60 ± 0.10
26 Jan	05:03	3.5 CAHA	V	1,200	22.24 ± 0.06
26 Jan	05:51	3.5 CAHA	U	2 x 1,800	21.90 ± 0.15
27 Jan	12:34	4.0 KPNO	R	5 x 900	22.50 ± 0.05
28 Jan	02:35	2.2 CAHA	U	2 x 1,500	≥ 21.0
28 Jan	03:18	2.2 CAHA	I	1,500	≥ 22.0
29 Jan	23:15	1.0 UPSO	R	6 x 1,200	≥ 22.5
13 Feb	05:00	2.5 NOT	B	18 x 600	24.23 ± 0.10
17 Feb	05:00	2.5 NOT	U	8 x 1,200	23.60 ± 0.15
18 Feb	05:00	2.5 NOT	I	10 x 900	23.65 ± 0.15
24 Jan	05:30	1.5 TCS	J	1,340	≥ 18.4
24 Jan	06:03	1.5 TCS	K'	450	≥ 17.5
30 Jan	05:50	3.5 CAHA	K'	2,310	≥ 19.5

Table 1: Observations were conducted at the 0.6-m Schmidt telescope of the Beijing Astronomical Observatory in Xinglong, China (0.6 BAO), the 1.04-m Sampurnanand telescope at Uttar Pradesh State Observatory, Nainital, India (1.0 UPSO), the IAC 0.82-m telescope at Observatorio del Teide, Tenerife, Spain (0.8 IAC), the 2.56-m Nordic Optical Telescope at Observatorio del Roque de los Muchachos, La Palma, Spain (NOT), the 1.5-m telescope of the Bologna Astronomical Observatory at Loiano, Italy (1.5 Loiano), the 3.5-m telescope at the German-Spanish Calar Alto Observatory (3.5 CAHA), the 2.2-m telescope at the German-Spanish Calar Alto Observatory (2.2 CAHA), the 4.0-m telescope at the Kitt Peak National Observatory (4.0 KPNO), and the 1.5-m Carlos Sánchez Telescope at the Observatorio del Teide, Tenerife, Spain (TCS).

Table 2. Power-law fits to the UBVRI observations of GRB 990123 for t > 3 h

Filter	δ	χ^2/dof
U	-1.41 ± 0.07	3.0/2
B	-1.33 ± 0.05	11.8/7
V	-1.30 ± 0.03	22.5/10
R	-1.21 ± 0.02	99.2/33
I	-1.32 ± 0.19	1.9/2

Table 3. Power-law fits to the R-band observations of GRB 990123

Time interval	δ	χ^2/dof
0 – 10 min	-2.12 ± 0.03	15.9/3
3 h – 2 d	-1.13 ± 0.02	23.5/27
2 d – 20 d	-1.66 ± 0.17	1.7/7

Table 4. Power-law fits to the UBVRI observations of GRB 990123 for 8.5 h < t < 2 d

Filter	δ	χ^2/dof
U	-1.37 ± 0.08	3.7/1
B	-1.26 ± 0.06	5.4/6
V	-1.20 ± 0.04	5.8/8
R	-1.13 ± 0.02	22.1/22
I	-1.14 ± 0.19	0.1/1