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The extraordinarily bright optical afterglow of GRB 991208 and its host galaxy

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Abstract. Broad-band optical observations of the extraordinarily bright optical afterglow of the intense gamma-ray burst GRB 991208 started ∼2.1 days after the event and continued until 4 Apr. 2000. The flux decay constant of the optical afterglow in the R-band is -2.30 ± 0.07 up to ∼5 days, which is very likely due to the jet effect, and it is followed by a much steeper decay with constant -3.2 ± 0.2, the fastest one ever seen in a GRB optical afterglow. A negative detection in several all-sky films taken simultaneously with the event, that otherwise would have reached naked eye brightness, implies either a previous additional break prior to ∼2 days after the occurrence of the GRB (as expected from the jet effect) or a maximum, as observed in GRB 970508. The existence of a second break might indicate a steepening in the electron spectrum or the superposition of two events, resembling GRB 000301C. Once the afterglow emission vanished, contribution of a bright underlying supernova was found on the basis of the late-time R-band measurements, but the light curve is not sufficiently well sampled to rule out a dust echo explanation. Our redshift determination of $z = 0.706$ indicates that GRB 991208 is at 3.7 Gpc (for $H_0 = 60$ km s^{-1} Mpc^{-1}, $\Omega_0 = 1$ and $\Lambda_0 = 0$), implying an isotropic energy release of 1.15 10^{53} erg which may be relaxed by beaming by a factor $>10^2$. Precise astrometry indicates that the GRB coincides within $0.2''$ with the host galaxy, thus supporting a massive star origin. The absolute magnitude of the galaxy is $M_B = -18.2$, well below the knee of the galaxy luminosity function and we derive a star-forming rate of (11.5 ± 7.1) $M_\odot$ yr^{-1}, which is much larger than the present-day rate in our Galaxy. The quasi-simultaneous broad-band photometric spectral energy distribution of the afterglow was determined ∼3.5 day after the burst (Dec. 12.0) implying a cooling frequency ν_c below the optical band, i.e. supporting a jet model with $p = -2.30$ as the index of the power-law electron distribution.

Key words. gamma rays: bursts – galaxies: general – cosmology: observations

1. Introduction

Gamma–ray bursts (GRBs) are flashes of cosmic high energy (∼1 keV – 10 GeV) photons (Fishman & Meegan 1995). For many years since their discovery in 1967 they remained without any satisfactory explanation, but 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 was detected. This led to the first detection of X-ray and optical afterglow for GRB 970228 (Costa et al. 1997; van Paradijs et al. 1997) and the determination of the cosmological distance scale for the bursts on the basis of the first spectroscopic measurements taken for GRB 970508, implying $z \geq 0.835$ (Metzger et al. 1997).

Subsequent observations in 1997-2000 have shown that about a third of the well localized GRBs can be associated with optical emission that gradually fades away over weeks to months. Now it is widely accepted that long duration GRBs originate at cosmological distances with energy releases of 10^{51}–10^{53} ergs. The observed afterglow satisfies the predictions of the "standard" relativistic fireball model, and the central engines that power these extraordinary events are thought to be the collapse of massive stars (see Piran 1999; van Paradijs et al. 2000 for a review).

The detection of GRB host galaxies is essential in order to understand the nature of hosts (morphology, star forming rates) and to determine the energetics of the bursts (redshifts) and offsets with respect to the galaxy centres. About 25 host galaxies have been detected so far, with redshifts z in the range 0.43–4.50 and star-forming rates in the range 0.5–60 $M_\odot$ year^{-1}. See Klose (2000), Castro-Tirado (2001) and references therein.

Here we report the detection of the optical afterglow from GRB 991208 as well as its host galaxy. This GRB was detected at 04:36 universal time (UT) on 8 Dec. 1999, with the Ulysses GRB detector, the Russian GRB Experiment (KONUS) on the Wind spacecraft and the Near Earth Asteroid Rendezvous (NEAR) detectors (Hurley et al. 2000) as an extremely intense, 60 s long GRB with a fluence >25 keV of 10^{-4} erg cm^{-2} and considerable flux above 100 keV. Radio observations taken on 1999 December 10.92 UT with the Very Large Array (VLA) at 4.86 GHz and 8.46 GHz indicated the presence of a compact source which became a strong candidate for the radio afterglow from GRB 991208 (Frail et al. 1999).

2. Observations and data reduction

We have obtained optical images centered on the GRB location starting 2.1 days after the burst (Table 1). Photometric observations were conducted with the 1.04-m Sampurnanand telescope at Uttar Pradesh State Observatory, Nainital, India (1.0 UPSO); the 1.34-m Schmidt telescope at Tautenburg, Germany (1.3 TBG); the 1.5-m telescope at Observatorio de Sierra Nevada (1.5 OSN), Granada, Spain; the 2.5-m Isaac Newton Telescope (2.5 INT), the 2.56-m Nordic Optical Telescope (NOT), the 3.5-m Telescopio Nazionale Galileo (3.5 TNG) and the 4.2-m William Herschel Telescope (4.2 WHT) at Observatorio del Roque de los Muchachos, La Palma, Spain; the 1.23-m, 2.2-m and 3.5-m telescopes at the German-Spanish Calar Alto Observatory (1.2, 2.2 and 3.5 CAHA respectively), Spain; the 3.5-m telescope operated by the Universities of Wisconsin, Indiana, Yale and the National Optical Astronomical Observatories (3.5-m WIYN) at Kitt Peak, USA; and the 6.0-m telescope at the Special Astrophisical Observatory of the Russian Academy of Sciences in Nizhnij Arhyz, Russia.

For the optical images, photometry was performed by means of SExtractor (Bertin & Arnouts 1996), making use of the corrected isophotal magnitude, which is appropriate for star-like objects. The DAOPHOT (Stetson 1987) profile-fitting technique was used for the magnitude determination on the later epoch images, when the source is much fainter. 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 in Henden (2000). Zeropoint uncertainties are also included in the given errors.

Prompt follow-up spectroscopy of the OA was attempted at several telescopes (Table 2), but we only achieved a reasonable signal-to-noise ratio (S/N) at the 6-m telescope SAO RAS using an integral field spectrograph MPFS (Dodonov et al. 1999a). One 2700-s spectrum and one 4500-s spectrum were obtained on 13 and 14 Dec. 1999 UT. On the latter, the observing conditions were good: the seeing was $\sim 1.5''$ (at a zenithal distance of 60°), and there was good transparency. We used 300 lines/mm grating blazed at 6000 Å giving a spectral resolution of about 5 Å/pixel and effective wavelength coverage of 4100–9200 Å. The spectrophotometric standards HZ44 and BD+75°325 (Oke et al. 1995) were used for the flux calibration.

3. Results and discussion

3.1. The optical afterglow

At the same location of the variable radiosource, a bright optical afterglow (OA) was identified on the images taken at Calar Alto, La Palma and Tautenburg (Castro-Tirado et al. 1999a,b). The astrometric solution was obtained using 16 USNO-A stars, and coordinates were $\alpha_{2000} = 16^{\rm h}33^{\rm m}53\overset{\rm s}{.}50; \delta_{2000} = +46°27'21.0''$ ($\pm 0.2''$). A comparison among optical images acquired on 10 and 11 Dec. allowed us to confirm the variability in intensity of the proposed OA. About 2.1 d after the burst, we measured $R = 18.7 \pm 0.1$ for the OA, and 19 h later we found $R = 19.60 \pm 0.03$. 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). Coincident (within errors) with the location of optical and radio afterglows, Shepherd et al. (1999) detected at millimeter wavelengths the brightest afterglow of a GRB reported so far. At 15 GHz and 240 GHz, the GRB 991208 afterglow was observed at Ryle (Pooley et al. 1999) and Pico Veleta (Bremer et al. 1999a,b), respectively.

Our B, V, R, I light curve (Fig. 2) shows that the source was declining in brightness. The optical decay slowed down in early 2000, indicating the presence of an underlying source of constant brightness: the host galaxy. The decay of previous GRB afterglows appears to be well characterized by a power law (PL) decay $F(t) \propto (t-t_0)^{\alpha}$, where $F(t)$ is the flux of the afterglow at time t since the onset of the event at t_0 and α is the decay constant. Assuming this parametric form and by fitting least square linear regressions to the observed magnitudes as function of time, we derive below the value of flux decay constant for GRB 991208. The fits to the B, V, R and I light curves are given in Table 3, but the poor quality of the PL fit is reflected in the relatively large reduced chi-squared values. This is specially noticeable in the R-band light curve,

Table 1. Journal of the GRB 991208 optical/NIR observations

Date of 1999 (UT)	Telescope	Filter	Integration time (s)	Magnitude
10.2708 Dec.	2.5 NOT	R	300	18.7 ± 0.1
10.2917 Dec.	2.5 INT	I	240	>15.5
11.2111 Dec.	1.3 TBG	I	900	18.75 ± 0.11
11.2111 Dec.	2.2 CAHA	R	600	19.60 ± 0.03
11.2507 Dec.	2.2 CAHA	R	600	19.61 ± 0.04
11.2792 Dec.	2.5 INT	R	300	19.70 ± 0.08
11.2833 Dec.	2.5 INT	I	300	19.2 ± 0.1
12.0208 Dec.	1.0 UPSO	I	2 × 200	19.9 ± 0.3
12.2000 Dec.	1.2 CAHA	B	300	>20.3
12.2056 Dec.	1.2 CAHA	V	300	>20.5
12.2181 Dec.	1.2 CAHA	R	300	20.0 ± 0.3
12.2229 Dec.	1.2 CAHA	V	500	20.7 ± 0.4
12.2299 Dec.	1.2 CAHA	B	500	21.3 ± 0.2
12.2500 Dec.	1.5 OSN	R	2 × 600	19.9 ± 0.5
12.2535 Dec.	1.2 CAHA	U	6 × 500	>19.8
12.2576 Dec.	1.5 OSN	I	300	19.8 ± 0.5
12.2604 Dec.	2.5 NOT	R	3 × 300	20.37 ± 0.05
12.2694 Dec.	2.5 NOT	I	3 × 300	19.95 ± 0.05
12.2757 Dec.	2.5 INT	B	500	21.40 ± 0.05
12.2792 Dec.	2.5 NOT	V	300	20.85 ± 0.05
12.2806 Dec.	2.5 INT	V	300	20.78 ± 0.06
12.2840 Dec.	2.5 INT	I	180	20.00 ± 0.17
12.2882 Dec.	3.5 TNG	R	500	20.0 ± 0.3
13.0000 Dec.	1.0 UPSO	I	3 × 600	20.3 ± 0.2
13.2604 Dec.	2.5 NOT	R	3 × 300	20.89 ± 0.04
13.2715 Dec.	2.5 INT	B	500	22.03 ± 0.06
13.2729 Dec.	2.5 NOT	I	3 × 300	20.34 ± 0.06
13.2764 Dec.	2.5 INT	V	180	21.36 ± 0.07
13.2799 Dec.	2.5 INT	I	300	20.26 ± 0.11
13.2833 Dec.	2.5 NOT	V	300	21.38 ± 0.07
13.2910 Dec.	3.5 TNG	R	360	20.8 ± 0.3
14.2708 Dec.	2.5 NOT	R	3 × 300	21.43 ± 0.04
14.2743 Dec.	2.5 INT	B	1000	22.31 ± 0.08
14.2778 Dec.	2.5 INT	U	535	>23.0
14.2792 Dec.	2.5 NOT	I	3 × 300	20.91 ± 0.07
14.2847 Dec.	3.5 TNG	R	600	21.40 ± 0.10
14.2875 Dec.	2.5 NOT	V	300	21.68 ± 0.10
15.2708 Dec.	2.5 NOT	R	3 × 300	21.97 ± 0.08
15.2833 Dec.	2.5 NOT	I	3 × 300	21.46 ± 0.16
15.2938 Dec.	2.5 NOT	V	2 × 300	>21.8
03.5319 Jan.	3.5 WIYN	R	600	>23.0
03.5507 Jan.	3.5 WIYN	I	600	>22.0
04.2292 Jan.	2.2 CAHA	R	2 × 900	>23.5
05.2292 Jan.	3.5 CAHA	R	2 × 1200	23.23 ± 0.13
06.2083 Jan.	2.2 CAHA	V	9 × 1200	23.83 ± 0.10
13.2097 Jan.	3.5 CAHA	R	3 × 1200	>23.1
13.2528 Jan.	3.5 CAHA	V	2 × 1200	>22.5
19.2604 Jan.	2.5 NOT	R	7 × 600	23.65 ± 0.13
29.2431 Jan.	4.2 WHT	I	2 × 900	>22.5
29.2604 Jan.	4.2 WHT	B	986	>23.6
13.2556 Feb.	3.5 TNG	B	3 × 1200	24.65 ± 0.04
17.2882 Feb.	3.5 TNG	V	2 × 1200	24.22 ± 0.09
31.8403 Mar.	6.0 SAO	V	1490	24.55 ± 0.16
31.8715 Mar.	6.0 SAO	I	360	23.46 ± 0.49
31.9028 Mar.	6.0 SAO	B	1795	25.19 ± 0.17
31.9583 Mar.	6.0 SAO	R	1260	24.27 ± 0.15
04.2083 Apr.	2.5 NOT	I	3800	23.3 ± 0.2
11.2708 Feb.	3.5 TNG	J	42 × 60	>22.0

Table 2. Journal of the GRB 991208 spectroscopic observations

Date of 1999 (UT)	Telescope	Wavelength range (A)	Exposure time (s)
12.2306 Dec.	2.2 CAHA	3550–4510	1800
12.2347 Dec.	3.5 CAHA	6000–10 000	1800
13.2083 Dec.	6.0 SAO	4100–9200	2700
14.2083 Dec.	6.0 SAO	4100–9200	4500
18.2431 Dec.	4.2 WHT	4000–9000	3600

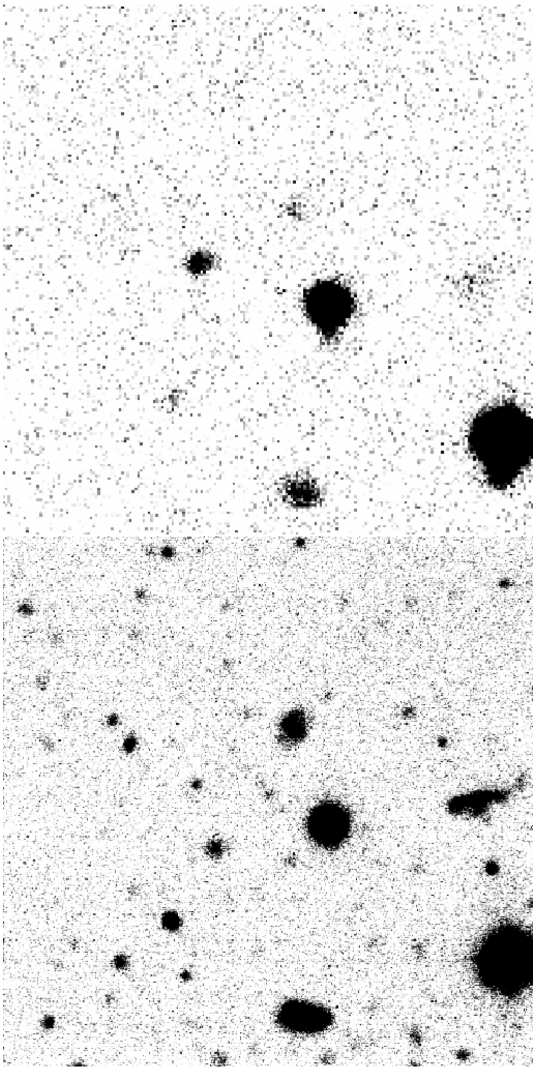

Fig. 1. Blue (B band) images of the GRB 991208 location. The frames were taken at the 2.5-m INT on 12 Dec. 1999 **a)**: *upper panel*, 3.9 d after the GRB, and at the 3.5-m TNG on 13 Feb. 2000 **b)**: *lower panel*, 36 days after the GRB. It shows the optical afterglow and the underlying galaxy close to the center of the image. Here only a $1'.1 \times 1'.1$ field of view is presented. The positions of both objects are consistent within the astrometric uncertainty ($0.2''$). North is at the top and east to the left. Limiting magnitudes were $B \sim 22.5$ and $B \sim 25.5$, respectively

due to the data obtained after one month, that will be discussed in Sect. 3.1.2.

Table 3. PL fits to the $BVRI$ observations of GRB 991208

Filter	α	χ^2/dof
B	-1.37 ± 0.04	24.6/3
V	-1.75 ± 0.07	16.0/6
R	-2.22 ± 0.04	91.5/11
I	-2.58 ± 0.12	19.3/8

Table 4. Broken PL fits to the RI observations of GRB 991208

Filter	α_1	χ^2/dof	α_2	χ^2/dof
R	-2.30 ± 0.07	3.9/6	-3.18 ± 0.22	5.7/3
I	-2.51 ± 0.27	0.4/3	-3.33 ± 0.39	1.1/3

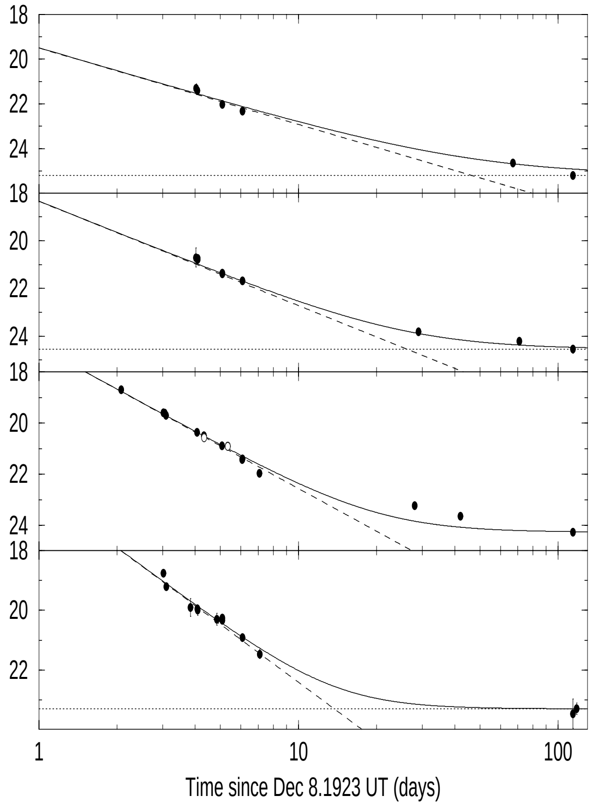

Fig. 2. The $BVRI$-band light-curves of the optical transient related to GRB 991208, including the underlying galaxy. Filled circles are our data are empty circles are data from Garnavich & Noriega-Crespo (1999) and Halpern & Helfand (1999). The dashed-line is the pure OA contribution to the total flux, according to the single power-law fits given in Table 2. The dotted line is the contribution of the host galaxy. The solid line is the combined flux (OA plus underlying galaxy)

3.1.1. The existence of two breaks

The R and I-band data up to $t_0 + 10$ days are better fitted by a broken PL with a break time $t_{\rm break} \sim 5$ days. For the B and V-band, such a fit is not possible due to the scarcity of the data in these bands. See Table 4. Hence, we adopt a value of $\alpha_1 = -2.30 \pm 0.07$ for 2 days $< (t - t_0) <$ 5 days and $\alpha_2 = -3.2 \pm 0.2$ for 5 days $< (t - t_0) <$ 10 days as flux decay constants in further discussions.

Further support for the existence of an additional break at $(t - t_0) < 2$ days in GRB 991208 comes from the extrapolation of the R-band data towards earlier epochs (Fig. 3), that predicts an optical flux that should have been seen with the naked eye by observers in Central Europe.

The optical event exceeding magnitude 11 could be detected by the Czech stations of the European Fireball

Network. Unfortunately, it was completely cloudy during the night of Dec. 8/9 in the Czech Republic, so none of the 12 stations of the network was able to take all-sky photographs. The first photographs after the GRB trigger were taken on Dec. 8, 16:25 UT, i.e. nearly 12 h after the event, and shows no object at its position brighter than mag $V \sim 10$. However, sky patrol films taken for meteor research were exposed in Germany during Dec. 8/9, 1999 but no OA exceeding $R \sim 4$ with a duration of 10 s or more is detected simultaneous to the GRB event. This upper limit derived from the films implies that this additional break in the power-law decay of GRB 991208 has to be present at 0.01 days $< (t-t_0) <$ 2 days although a maximum in the light curve similar to GRB 970508 (Castro-Tirado et al. 1998) cannot be excluded.

The flux decay of GRB 991208 is one of the steepest of all GRBs observed so far (Sagar et al. 2000). Before deriving any conclusion from the flux decays of these GRBs, we compare them with other well studied GRBs. Most OAs exhibit a single power-law decay index, generally ~ -1.2, a value reasonable for spherical expansion of a relativistic blast wave in a constant density interstellar medium (Mészáros & Rees 1997; Wijers et al. 1997; Waxman 1997; Reichart 1997). For other bursts, like GRB 990123, the value of $\alpha = -1.13 \pm 0.02$ for the early time (3 hr to 2 day) light curve becomes -1.75 ± 0.11 at late times (2–20 day) (Kulkarni et al. 1999; Castro-Tirado et al. 1999c; Fruchter et al. 1999) while the corresponding slopes for GRB 990510 are -0.76 ± 0.01 and -2.40 ± 0.02 respectively with the $t_{\rm break} \sim 1.57$ day (Stanek et al. 1999; Harrison et al. 1999). If the steepening observed in both cases is due to beaming, then one may conclude that it occurs within <2 days of the burst.

Rapid decays in OAs have been seen in GRB 980326 with $\alpha = -2.0 \pm 0.1$ (Bloom et al. 1999a), GRB 980519 with $\alpha = -2.05 \pm 0.04$ (Halpern et al. 1999), GRB 990510 with $\alpha = -2.40 \pm 0.02$ (Stanek et al. 1999; Harrison et al. 1999) and GRB 000301C with $\alpha = -2.2 \pm 0.1$ (Masetti et al. 2000; Jensen et al. 2001; Rhoads & Fruchter 2001), and have been interpreted as the sideways expansion of a jet (Rhoads 1997, 1999; Mészáros & Rees 1999). For GRB 991208, $\alpha_1 = -2.30 \pm 0.07$ and we therefore argue that the observed steep decay in the optical light curve up to ~5 days may be due to a break which occurred before our first optical observations starting ~2.1 day after the burst. The break is expected in several physical models, but beaming is the most likely cause in GRB 991208 taking into account that the rapid fading of optical afterglows is considered as evidence for beaming in GRBs (Huang et al. 2000).

According to the current view, the forward external shock wave would have led to the afterglow as observed in all wavelengths. The population of electrons is assumed to be a power-law distribution of Lorentz factors $\Gamma_{\rm e}$ following ${\rm d}N/{\rm d}\Gamma_{\rm e} \propto \Gamma_{\rm e}^{-p}$ above a minimum Lorentz factor $\Gamma_{\rm e} \geq \Gamma_{\rm m}$, corresponding to the synchrotron frequency $\nu_{\rm m}$. The value of p can be determined taking into account the occurrence of the *jet effect*: the break due to a lateral expansion in

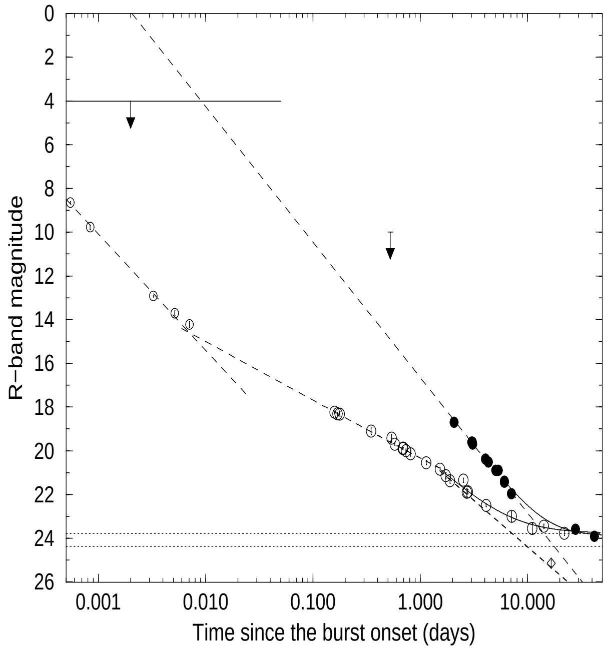

Fig. 3. Comparison of the two brightest optical GRB afterglows detected so far: GRB 990123 (empty circles, from Castro-Tirado et al. 1999c) and GRB 991208 (filled circles, from this paper). The extrapolation of the GRB 991208 R-band data towards earlier epochs predicts an optical flux that should have been seen at naked eye by observers in Central Europe. However, the upper limit ($R \sim 4$) derived from simultaneous sky patrol films implies that either a break in the power-law decay or a maximum in the light curve has to be present at $0.01 < T < 2$ days. The dotted lines are the constant contribution of the two host galaxies, $R \sim 23.9$ and 24.3 respectively. The dashed-lines are the pure OAs contributions to the total fluxes. The solid lines (only shown here for clarity after $T > 5$ days) are the combined fluxes (OA plus underlying galaxy on each case)

the decelerating jet occurs when the initial Lorentz factor Γ drops below θ_0^{-1} (with θ_0 the initial opening angle), i.e. the observer "sees" the edge of the jet. A change in the initial power-law decay exponent α_0 (unknown to us) from $\alpha_0 = 3(1-p)/4$ to $\alpha_1 = -p$ (for $\nu_{\rm m} < \nu < \nu_{\rm c}$), or from $\alpha_0 = (2-3p)/4$ to $\alpha_1 = -p$ (for $\nu \geq \nu_{\rm c}$) is expected (Rhoads 1997, 1999). If this is the case, then $p = -\alpha_1 = 2.30 \pm 0.07$, in the observed range for other GRBs.

Whether the jet was expanding into a constant density medium or in an inhomogeneus medium (Chevalier & Li 1999; Wei & Lu 2000) cannot be determined with our data alone, as we do not have information on α_0. For a density gradient of $s = 2$, as expected from a previously ejected stellar wind ($\rho \propto r^{-s}$), the light curve should steepen by $\Delta\alpha = (\alpha_1 - \alpha_0) = (3-s)/(4-s) = 0.5$ whereas $\Delta\alpha = 0.75$ for a constant density medium.

What is the reason for the second break observed in GRB 991208 after ~5 days? The passage of the cooling frequency $\nu_{\rm c}$ through the optical band (that would steepen the light curve by $\Delta\alpha \sim 0.25$, Sari et al. 1998) can be discarded: following Sari et al. (1999), if $\nu < \nu_{\rm c}$ then we should expect a spectral index β ($F_\nu \propto \nu^{-\beta}$) such as

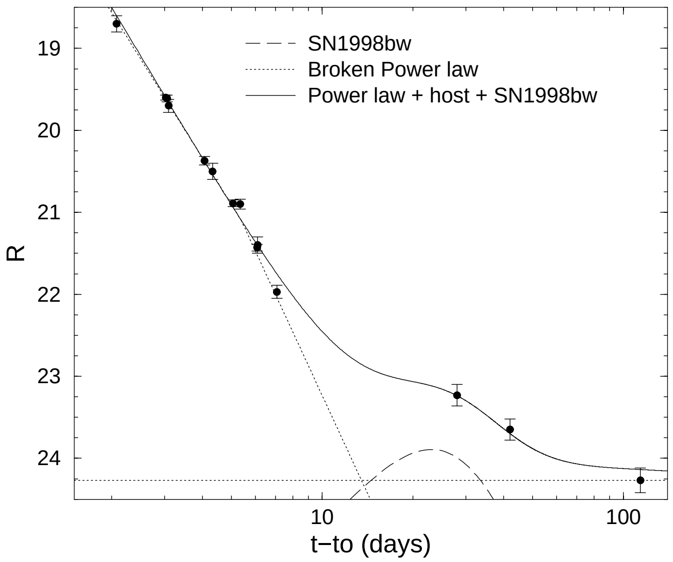

Fig. 4. The GRB 991208 R-band light curve (solid line) fitted with a SN1998 bw-like component at $z = 0.706$ (long dashed line) superposed on the broken power-law OA light curve displaying the second break at $t_{\rm break} \sim 5$ d (with $\alpha_1 = -2.3$ and $\alpha_2 = -3.2$, short dotted lines) and the constant contribution of the host galaxy ($R = 24.27 \pm 0.15$, dotted line)

$\beta = (p-1)/2 = 0.65 \pm 0.04$ and if $\nu > \nu_{\rm c}$ then $\beta = p/2 = 1.15 \pm 0.04$ which is compatible with $F_\nu \propto \nu^{-1.05\pm0.08}$ on 12 Dec. (see Sect. 3.3). Hence we conclude that $\nu_{\rm c}$ has already passed the optical band 4 days after the burst onset.

The difference between the mid and late time decay slopes is $\Delta\alpha = (\alpha_2 - \alpha_1) = 0.9 \pm 0.3$. A possible explanation could be two superposed events: a major burst followed by a minor burst, expected from some SN-shock models (Mészaros et al. 1998) similar to that proposed for GRB 000301C (Bhargavi & Cowsik 2000). Li & Chevalier (2001) find that a spherical wind model (with $\rho \propto r^{-2}$) and a jet model fit the radio data when using a steepening of the electron spectrum, invoking a non-standard, broken PL around a break Lorentz factor $\Gamma_{\rm break}$: $dN_{\rm e}/d\Gamma = C_1\Gamma^{-p_1}$ if $\Gamma_{\rm min} < \Gamma < \Gamma_{\rm break}$ and $dN_{\rm e}/d\Gamma = C_2\Gamma^{-p_2}$ if $\Gamma > \Gamma_{\rm break}$. They derive $p_1 = 2.0$ and $p_2 = 3.3$, the latter value being consistent with $-\alpha_2$.

3.1.2. The late–time light curve: Another underlying SN?

If an underlying supernova (SN) was present in the GRB 991208 light curve, it is expected to peak at $\sim$15(1+z) days $\sim$25 days. GRB 990128 is a good candidate for such a search thanks to the rapid decay. Indeed, the late–time light curve in the optical band (specially in the R-band) cannot be acceptably fitted just with the power-law decline expected for the OA plus the constant contribution of the host galaxy (χ^2/dof = 8.32). The data is much better fitted when considering a third component, a type Ic SN1998bw-like component (Galama et al. 1998) at $z = 0.706$ (χ^2/dof = 1.88), see Fig. 4. We have used SN1998bw because of its likely relationship to GRB 980425.

Thus, GRB 991208 would be the sixth event for which contribution from a SN is proposed, after GRB 970228 (Reichart 1999; Galama et al. 2000b), GRB 970508 (Sokolov et al. 2001a), GRB 980326 (Castro-Tirado & Gorosabel 1999; Bloom et al. 1999a), GRB 990712 (Hjorth et al. 1999; Sahu et al. 2000) and GRB 000418 (Klose et al. 2000; Dar & De Rújula 2001). This reinforces the GRB-SN relationship for some long duration bursts and supports the scenario in which the death of a massive star produces the GRB in the "collapsar" model (MacFadyen & Woosley 1999). Our results do not support the "supranova" model (Vietri & Stella 1998) for this event as the SN should have preceeded the GRB by few months.

Could the observations be explained by a dust echo instead? Esin & Blandford (2000) presented an alternative explanation for the excess of red flux observed 20–30 days after GRB 970228 and GRB 980326, being scattering off dust grains, peaking around $\sim$4000 Å in the rest frame (i.e. in the R-band at $z = 0.706$, as observed in GRB 991208). On the basis of $VRIJK$ observations for GRB 970228, Reichart (2001) concluded that the late-time afterglow of that event cannot be explained by a dust echo. For GRB 991208, only V- and R-band data (plus an upper limit in the I-band) are available at the time of the maximum, i.e. the light curve is not sufficiently well sampled to distinguish between a SN and a dust echo.

3.2. The host galaxy

Evidence for a bright host galaxy came from the BTA/MPSF 4500-s spectrum of the GRB 991208 optical transient taken on 14 Dec. (see Fig. 5). We found four emission lines at λ = 6350 Å, 8300 Å, 8550 Å, and 8470 Å, with the most likely identifications of these emission lines being: [OII] 3727 Å, H_β 4861 Å, [OIII] 4959 Å, 5007 Å at a redshift of $z = 0.7063 \pm 0.0017$ (Dodonov et al. 1999b), a value confirmed by other measurements taker late (Djorgovski et al. 1999). Line parameters are measured with a Gaussian fit to the emission line and a flat fit to the continuum.

Considering the redshift of $z = 0.7063 \pm 0.0017$, $H_0 = 60$ km s^{-1} Mpc^{-1}, $\Omega_0 = 1$ and $\Lambda_0 = 0$, the luminosity distance to the host is $d_{\rm L} = 1.15\ 10^{28}$ cm, implying an isotropic energy release of $1.15\ 10^{53}$ erg. Taking into accout the time of the break, $t_{\rm break} < 2$ d, this implies an upper limit on the jet half-opening angle $\theta_0 < 8^\circ\ n^{1/8}$ with n the density of the ambient medium (in cm^{-3}) (see Wijers & Galama 1999), and thus the energy release should be lowered by >100, i.e. the energy released is <$1.15\ 10^{51}$ erg.

For the galaxy, which is present in the late images (March-April 2000), the astrometric solution also obtained using the same 16 USNO-A stars was $\alpha_{2000} = 16^{\rm h}33^{\rm m}53\overset{\rm s}{.}53$; $\delta_{2000} = +46°27'21.0''$ ($\pm0.2''$), which is consistent with the OA position. See also Fruchter et al. (2000).

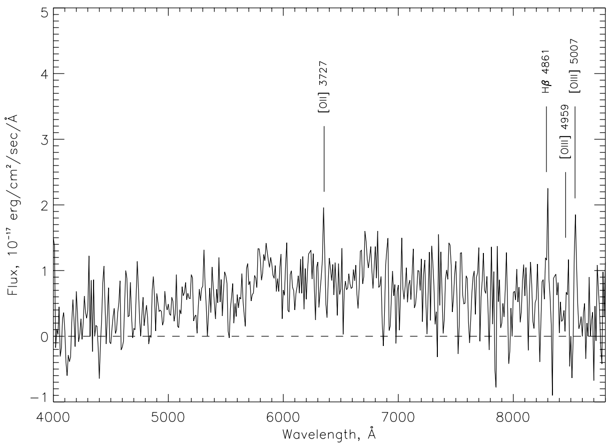

Fig. 5. The BTA/MPSF optical 4500-s spectrum of the GRB 991208 afterglow (on Dec. 14.14, 1999 UT) in the 4000–8800 Å spectral range. The spectrum has been boxcar smoothed with a 10 Å window. The detection of the four emission lines led to a redshift of $z = 0.7063 \pm 0.0017$, that of the host galaxy

Table 5. Journal of the GRB 991208 line identifications

Line ID	Fluxes (10^{-16} erg cm^{-2} s^{-1})	$-EW$ (Å)	$FWHM$ (Å)
[OII] 3727	(1.79 ± 0.22)	20	15.4 ± 2.0
H_β	(3.84 ± 0.33)	93	22.3 ± 2.2
[OIII] 4958.9	(1.61 ± 0.32)	80	18.7 ± 4.5
[OIII] 5006.9	(4.90 ± 0.33)	244	20.8 ± 1.9

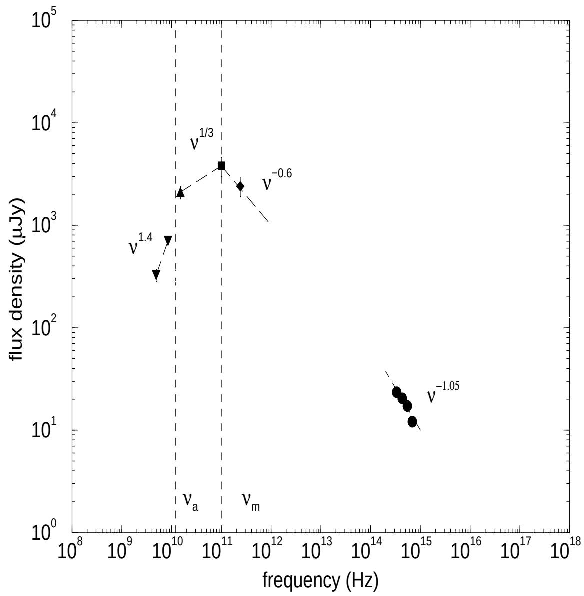

Fig. 6. The multiwavelength spectrum of GRB 991208 afterglow on Dec. 12.0 UT, 1999. Circles are the extrapolation of the $BVRI$ measurements following the power-law derived in this paper. The diamond is the Pico Veleta measurement (Bremer et al. 1999a,b), the square is the OVRO data point (Shepherd 1999), the triangle-up is the flux density obtained at the Ryle telescope (Pooley et al. 1999) and the triangles-down are the VLA data points (Frail et al. 1999; Hurley et al. 2000). The correction for galactic extinction has been considered taking into account $E(B-V) = 0.016$ from (Schlegel et al. 1998). The long dashed lines are the fits to the multiwavelength spectrum. Rough estimates of the self-absorption (ν_a) and synchrotron frequencies (ν_m) are also indicated

Our broad-band measurements of $B = 25.19 \pm 0.17$, $V = 24.55 \pm 0.16$, $R = 24.27 \pm 0.15$ on 31.9 Mar. and $I = 23.3 \pm 0.2$ on 4.2 Apr., once dereddened by the Galactic extinction, imply a spectral distribution $F_\nu \propto \nu^{-\beta}$ with $\beta = +1.45 \pm 0.33$ (χ^2 per degree of freedom, χ^2/dof = 1.20). See Sokolov et al. (2000) for further details. The unobscured flux density at 7510 Å, the redshifted effective wavelength of the B-band, is ∼0.65 μJy, corresponding to an absolute magnitude of $M_B = -18.2$, well below the knee of the galaxy luminosity function, $M_B^* \sim -20.6$ (Schechter 1976).

The star-forming rate (SFR) can be estimated in different ways. Again, we have assumed $H_0 = 60$ km s^{-1} Mpc^{-1} and $\Omega_0 = 1$, $\Lambda_0 = 0$. From the H_β flux which is (3.84 ± 0.33) 10^{-16} erg cm^{-2} s^{-1}, this corresponds to (18.2 ± 0.6) $M_\odot$ yr^{-1} (Pettini et al. 1998). From the [O II] 3727 Å flux (Kennicutt 1998), which is (1.79 ± 0.22) 10^{-16} erg cm^{-2} s^{-1} we get (4.8 ± 0.2) $M_\odot$ yr^{-1}. The mean value, (11.5 ± 7.1) $M_\odot$ yr^{-1}, is much larger than the present-day rate in our Galaxy. In any case, this estimate is only a lower limit on the SFR due to the unknown rest frame host galaxy extinction. See also Sokolov et al. (2001b).

3.3. The multiwavelength spectrum on Dec. 12.0

We have determined the flux distribution of the GRB 991208 OA on Dec. 12.0, 1999 UT by means of our broad-band photometric measurements (Dec. 12.2) and other data points at mm and cm wavelengths (Dec. 11.6-11.8) (Fig. 6). We fitted the observed flux distribution with a power law $F_\nu \propto \nu^{-\beta}$, where F_ν is the flux at frequency ν, and β is the spectral index. Optical flux at the wavelengths of B, V, R and I passbands has been derived subtracting the contribution of the host galaxy and assuming a reddening $E(B-V) = 0.016$ (Schlegel et al. 1998). In converting the magnitude into flux, the effective wavelengths and normalizations given in Bessell (1979) and Bessell & Brett (1988) were used. The flux densities are 11.5, 16.7, 22.0 and 24.2 μJy at the effective wavelengths of B, V, R and I passbands, not corrected for possible intrinsic absorption in the host galaxy. The fit to the optical data $F_\nu \propto \nu^{-\beta}$ gives $\beta = +1.05 \pm 0.09$ (χ^2/dof = 5.7). This is about 2σ above the value of $\beta = +0.77 \pm 0.14$ given on Dec. 16.6 with the Keck telescope (Bloom et al. 1999b) and $\beta = +1.4 \pm 0.4$ for the spectral index between optical to IR wavelengths (that differs from the one given by Sagar et al. 2000) when considering α_2.

From the maximum observed flux (Shepherd et al. 1999), we derive a rough value of $\nu_m \sim 100$ GHz. The low-frequency spectrum below ν_m ($F_\nu \propto \nu^{1/3}$) is in agreement with the expected tail of the synchrotron radiation plus a self absorption that becomes important below a critical frequency $\nu_a \sim 13$ GHz, taking into account that $F_\nu \propto \nu^{1.4}$ in the range 4.86–8.46 GHz (Frail et al. 1999), deviating from $F_\nu \propto \nu^{1/3}$ as seen for 15 GHz $< \nu <$ 100 GHz (Pooley et al. 1999). Much more accurate estimates for ν_a and ν_m are given by Galama et al. (2000a). Above ν_m, the IRAM observations (Bremer et al. 1999a,b) indicate a $F_\nu \propto \nu^{-0.6}$, with a cooling frequency 3 10^{11} GHz $< \nu_c <$ 3 10^{14} GHz. Then we expect a slope between ν_m and ν_c of $\beta = (p-1)/2 = 0.68 \pm 0.06$, consistent with the observed value. As we have already mentioned, if the $p = 2.3$ jet model is correct, by this time (Dec. 12.0 UT), the cooling break should be already below the optical band, with an optical synchrotron spectrum $F_\nu \propto \nu^{-p/2} = \nu^{-1.15}$ that is in agreement with our optical data ($\beta = -1.05 \pm 0.09$). Therefore our Dec. 12.0 observations support a jet model with $p = 2.30 \pm 0.07$, marginally consistent with $p = 2.52 \pm 0.13$ as proposed by Galama et al. (2000a) on the basis of a fit to the multiwavelength spectra from the radio to the R-band data.

4. Conclusion

Most currently popular theories imply a direct correlation between star formation and GRB activity. How does GRB 991208 fit into this picture? The angular coincidence of the OA and the faint host argues against a compact binary merger origin of this event (Fryer et al. 1999) and in favor of the involvement of a massive star (Bodenhaimer & Woosley 1983; Woosley 1993; Dar & De Rújula 2001). The very rapid photometric decline of the afterglow of GRB 991208 provided hope for the detection of the much fainter light contamination from the underlying supernova, what we have confirmed on the basis of the late-time R-band measurements, thus giving further support to the massive star origin. There are still many unsolved riddles about GRBs, like the second break in the light curve of this event, i.e. responsible for the steep decay seen after 5 days. The community continues to chase GRB afterglows, and with every new event we make progress by finding more clues and creating even more new puzzles.

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