The Astrophysical Journal, 609:L5–L8, 2004 July 1

SN 2003lw AND GRB 031203: A BRIGHT SUPERNOVA FOR A FAINT GAMMA-RAY BURST

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Received 2004 April 14; accepted 2004 May 21; published 2004 May 27

ABSTRACT

Optical and near-infrared observations of the gamma-ray burst GRB 031203, at $z = 0.1055$, are reported. A very faint afterglow is detected superposed onto the host galaxy in our first infrared *JHK* observations, carried out ∼9 hr after the burst. Subsequently, a rebrightening is detected in all bands, peaking in the *R* band about 18 rest-frame days after the burst. The rebrightening closely resembles the light curve of a supernova like SN 1998bw, assuming that the GRB and the SN went off almost simultaneously, but with a somewhat slower evolution. Spectra taken close to the maximum of the rebrightening show extremely broad features as in SN 1998bw. The determination of the absolute magnitude of this SN (SN 2003lw) is difficult owing to the large and uncertain extinction, but likely this event was brighter than SN 1998bw by 0.5 mag in the *VRI* bands, reaching an absolute magnitude $M_V = -19.75 \pm 0.15$.

Subject headings: gamma rays: bursts — supernovae: individual (SN 2003lw)

Online material: color figures

1. INTRODUCTION

In recent years, an extensive optical and near-infrared (NIR) follow-up of gamma-ray bursts (GRBs) has revealed a physical connection between a fraction of long-duration GRBs and core-collapse supernovae (SNe). First, SN 1998bw was discovered spatially and temporally coincident with GRB 980425 (Galama et al. 1998; Kulkarni et al. 1998). This event, however, was rather different from classical, cosmological GRBs, being severely underenergetic and lacking an optical afterglow. Then, SN 2003dh was detected in the afterglow of GRB 030329 (Stanek et al. 2003; Hjorth et al. 2003). Both SNe showed broad bumps in their spectra, indicating very large expansion velocities (up to 30,000 km s^{-1}), and were extremely bright. These highly energetic SNe are often designed as hypernovae (e.g., Iwamoto et al. 1998). Finally, bumps in the light curves of several afterglows, peaking ∼20 days after the GRB, have been interpreted as being due to SNe outshining the afterglow light, based on their brightness, temporal evolution, and colors (e.g., Bloom et al. 1999; Garnavich et al. 2003). The bumps resemble the light curve of SN 1998bw, with a certain scatter in the brightness and rise time (e.g., Zeh et al. 2004). Spectroscopic confirmation that the bump of GRB 021211 has an SN spectrum (SN 2002lt; Della Valle et al. 2003) supports this conclusion. These observations indicate that the GRB/SN association is common.

GRB 031203 was discovered by *INTEGRAL* on 2003 December 3.91769 UT (Götz et al. 2003), with a duration of ∼30 s and a peak flux of 1.3×10^{-7} ergs cm^{-2} s^{-1} (20–200 keV; Mereghetti & Götz 2003). The precise and fast dissemination of the GRB coordinates by the *INTEGRAL* burst alert system (Mereghetti et al. 2003) facilitated an effective search for the afterglow. We also immediately activated our Target of Opportunity program at ESO, starting NIR observations at the New Technology Telescope (NTT) 7 hr after the GRB (Zerbi et al. 2003). The X-ray and radio afterglows were soon discovered (Santos-Lleo & Calderon 2003; Frail 2003). A compact galaxy, located at a consistent position, was proposed to be the GRB host galaxy by Prochaska et al. (2003). The redshift was $z = 0.1055 \pm 0.0001$ (Prochaska et al. 2003, 2004), making GRB 031203 the second closest burst after GRB 980425 at $z = 0.0085$ (Galama et al. 1998). Vaughan et al. (2004) discovered a scattered, expanding X-ray halo that was due to the reflection of the burst and/or early afterglow light from Galactic dust grains, thus providing an (indirect) measurement of the X-ray flux at the earliest stages after the burst onset.

Given the low redshift of this event, the isotropic-equivalent burst energy is extremely low,[13] $E_{\rm iso} \sim 3 \times 10^{49}$ ergs (20–2000 keV; Watson et al. 2004; Prochaska et al. 2004), well below the standard reservoir of $\sim 2 \times 10^{51}$ ergs of normal GRBs (Frail et al. 2001; Bloom et al. 2003). Only GRB 980425 (Galama et al. 1998) and XRF 020903 (Sakamoto et al. 2004) were less energetic.

Based on photometric monitoring of the host galaxy, several groups have reported evidence of an SN associated with GRB 031203 (Bersier et al. 2004; Thomsen et al. 2004; Cobb et al.

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[13] We adopt a cosmology with $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$ (*WMAP* results). At $z = 0.1055$, the luminosity distance is $D = 477$ Mpc, and the distance modulus is $\mu = 38.42$ mag.

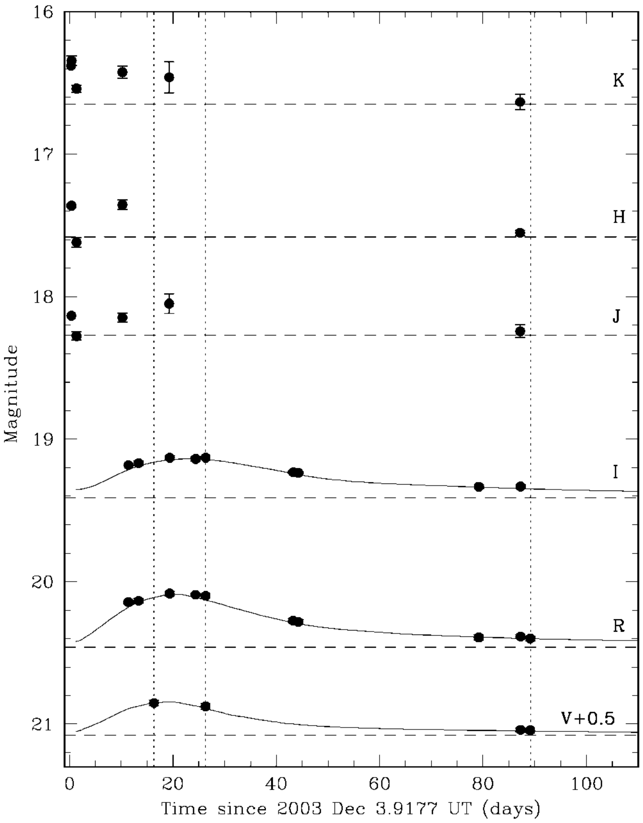

FIG. 1.—Optical and NIR light curves of GRB 031203 (*circles*). Error bars indicate the amount of relative errors only (Table 1). The solid curves show the evolution of SN 1998bw (Galama et al. 1998; McKenzie & Schaefer 1999), rescaled at $z = 0.1055$, stretched by a factor 1.1, extinguished with $E_{B-V} = 1.1$, and brightened by 0.5 mag. The dashed lines indicate the host galaxy contribution. The vertical dotted lines mark the epochs of our spectra. [*See the electronic edition of the Journal for a color version of this figure.*]

2004; Gal-Yam et al. 2004). After the ultimate confirmation, coming from spectroscopic observations and reported by our group (Tagliaferri et al. 2004), the IAU named this event SN 2003lw.

2. OBSERVATIONS AND DATA REDUCTION

Photometry.—We observed the field of GRB 031203 ≈7 hr after the trigger, to search for the NIR afterglow, using SofI on the ESO NTT. Subsequent imaging with ISAAC on the ESO VLT showed a varying source coincident with the putative host galaxy of GRB 031203: the total flux had dimmed in the *J*, *H*, and *K* filters by a few tenths of a magnitude (see Fig. 1). We therefore started a campaign to monitor the light curve of the event, searching for an SN rebrightening. The observing log is presented in Table 1.

Image reduction and analysis were performed following the standard procedures, by means of both aperture photometry and point-spread function (PSF)–matched image subtraction. To avoid saturation from a nearby bright star, the exposure time was always kept short. In some cases, occulting bars were used to cover the bright star (showing that the effect was negligible). Optical and NIR photometry were calibrated against Landolt standard stars and the Two Micron All Sky Survey, respectively. To focus on the issue of variability, in Table 1 we list just the relative photometry with respect to a reference epoch. We should also note that the host galaxy spectrum is dominated by prominent emission lines. This may lead to relatively large offsets when comparing results from other instruments, owing to unavoidable small differences in the filter profiles and CCD efficiencies.

TABLE 1
SUMMARY OF PHOTOMETRIC OBSERVATIONS

UT Start	Seeing (arcsec)	Instrument	Band	Magnitude[a]
2003 Dec 20.247	0.3	FORS2	*V*	−0.023 ± 0.020
2003 Dec 30.250	0.5	FORS1	*V*	**20.37 ± 0.05**
2004 Feb 29.193	0.7	FORS1	*V*	0.165 ± 0.012
2004 Mar 02.064	0.7	FORS1	*V*	0.169 ± 0.015
2003 Dec 15.314	0.6	FORS1	*R*	**20.14 ± 0.03**
2003 Dec 17.284	0.7	FORS1	*R*	−0.009 ± 0.016
2003 Dec 23.295	0.5	FORS1	*R*	−0.060 ± 0.016
2003 Dec 28.296	0.6	FORS1	*R*	−0.051 ± 0.010
2003 Dec 30.241	0.5	FORS1	*R*	−0.044 ± 0.013
2004 Jan 16.171	0.8	FORS1	*R*	0.130 ± 0.013
2004 Jan 17.185	0.5	FORS1	*R*	0.139 ± 0.014
2004 Feb 21.101	0.7	FORS1	*R*	0.248 ± 0.019
2004 Feb 29.198	0.7	FORS1	*R*	0.242 ± 0.012
2004 Mar 02.069	0.6	FORS1	*R*	0.255 ± 0.016
2003 Dec 15.321	0.5	FORS1	*I*	**19.18 ± 0.03**
2003 Dec 17.291	0.6	FORS1	*I*	−0.014 ± 0.015
2003 Dec 23.300	0.4	FORS1	*I*	−0.052 ± 0.013
2003 Dec 28.301	0.6	FORS1	*I*	−0.044 ± 0.015
2003 Dec 30.245	0.4	FORS1	*I*	−0.052 ± 0.009
2004 Jan 16.177	0.6	FORS1	*I*	0.050 ± 0.008
2004 Jan 17.179	0.6	FORS1	*I*	0.054 ± 0.007
2004 Feb 21.107	0.5	FORS1	*I*	0.151 ± 0.013
2004 Feb 29.203	0.8	FORS1	*I*	0.150 ± 0.013
2003 Dec 04.288	0.9	SofI	*J*	**18.13 ± 0.034**
2003 Dec 05.258	0.5	ISAAC	*J*	0.143 ± 0.030
2003 Dec 15.140	1.1	SofI	*J*	0.014 ± 0.032
2003 Dec 24.191	1.0	SofI	*J*	−0.084 ± 0.069
2004 Feb 28.111	0.5	ISAAC	*J*	0.110 ± 0.045
2003 Dec 04.300	0.9	SofI	*H*	**17.36 ± 0.042**
2003 Dec 05.271	0.5	ISAAC	*H*	0.257 ± 0.035
2003 Dec 14.148	0.9	SofI	*H*	−0.006 ± 0.033
2004 Feb 28.104	0.5	ISAAC	*H*	0.190 ± 0.019
2003 Dec 04.204	0.9	SofI	*K*	**16.38 ± 0.036**
2003 Dec 04.312	0.8	SofI	*K*	−0.036 ± 0.033
2003 Dec 05.267	0.5	ISAAC	*K*	0.161 ± 0.025
2003 Dec 14.154	0.8	SofI	*K*	0.046 ± 0.044
2003 Dec 23.188	1.0	SofI	*K*	0.082 ± 0.107
2004 Feb 28.095	0.5	ISAAC	*K*	0.255 ± 0.055
2003 Dec 24.507	1.5	MAGNUM	*I*	19.16 ± 0.03
2004 Jan 06.447	1.4	MAGNUM	*I*	19.16 ± 0.03
2003 Dec 24.503	1.1	MAGNUM	*K*	16.61 ± 0.04
2004 Jan 06.445	1.1	MAGNUM	*K*	16.58 ± 0.04

[a] Magnitudes are given relative to the boldface epoch.

Additional *K* and *I* photometry was acquired with the 2 m Multicolor Active Galactic Nuclei Monitoring (MAGNUM) telescope of the University of Tokyo (Yoshii et al. 2003), located in the Hawaii Islands. Although the different shape of the MAGNUM and ESO *I* filters (particularly critical due to the presence of the bright Hα line in the blue filter wing) makes it difficult to compare the results, the data are in good agreement (Table 1). For consistency, these data are not plotted in Figure 1.

Spectroscopy.—Moderate-resolution spectra (FWHM ≈ 10 Å) were taken with the VLT on 2003 December 20 (FORS2), 2003 December 30 (FORS1), and 2004 March 1 (FORS1). Flux calibration was achieved by observing spectrophotometric stars. After comparing synthetic magnitudes calculated from our spectra with the photometry, we introduced a correction to account for light loss outside the slit. To ensure a sound relative calibration between the spectra, we also checked that the fluxes of the host galaxy emission lines did not vary. A detailed discussion of the spectroscopy and of the host galaxy will be presented elsewhere (G. Chincarini et al. 2004, in preparation [hereafter C04]).

3. RESULTS AND DISCUSSION

In Figure 1, we show the light curves of GRB 031203. Early-time NIR photometry shows a dimming in all bands between

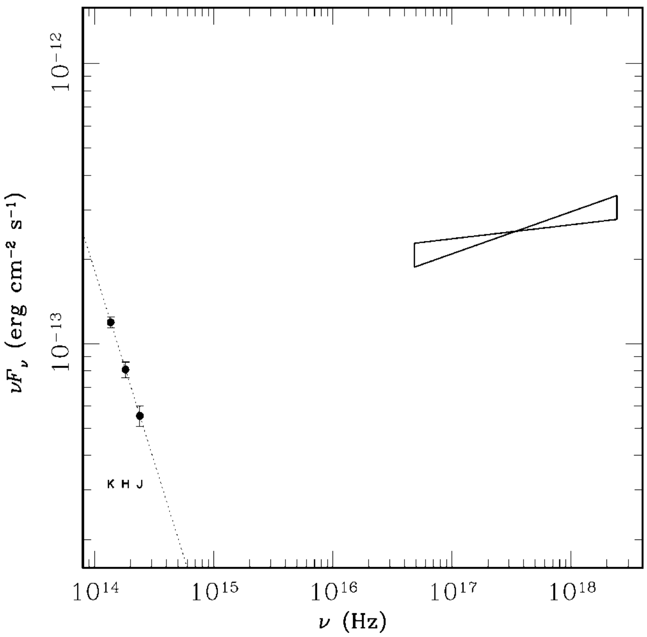

FIG. 2.—Spectral energy distribution of the afterglow of GRB 031203 on 2003 December 4.3 UT (9 hr after the trigger). The NIR values are calculated from our data by subtracting the host contribution and assuming $E_{B-V} = 1.1$. The NIR spectral index is $\beta = 2.36 \pm 0.02$ ($F_\nu \propto \nu^{-\beta}$). The X-ray spectrum is from Watson et al. (2004; reported at $t = 9$ hr using the X-ray decay slope), who find $N_{\rm H} = 8.8 \times 10^{21}$ cm^{-2} and $\beta_{\rm X} = 0.90 \pm 0.05$. [*See the electronic edition of the Journal for a color version of this figure.*]

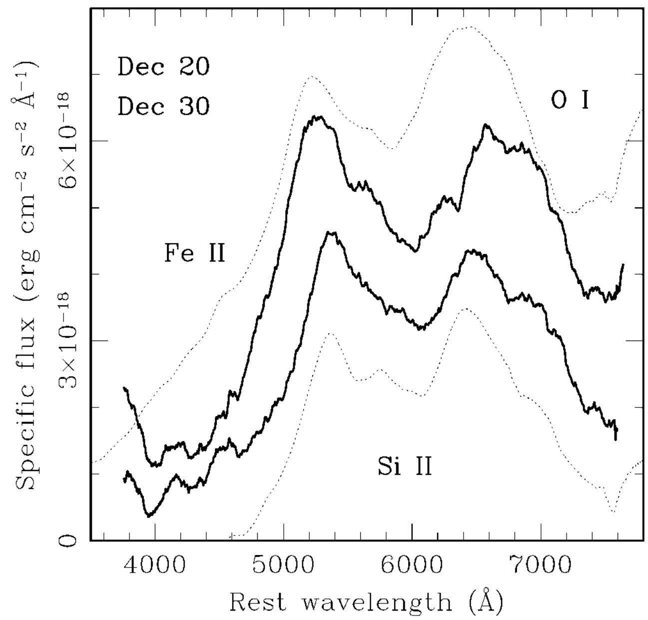

FIG. 3.—Spectra of SN 2003lw, taken on 2003 December 20 and 30 (*solid lines*), smoothed with a boxcar filter 250 Å wide. Dotted lines show the spectra of SN 1998bw (from Patat et al. 2001), taken on 1998 May 9 and 19 (13.5 and 23.5 days after the GRB, or 2 days before and 7 days after the *V*-band maximum, respectively), extinguished with $E_{B-V} = 1.1$ and a Galactic extinction law (Cardelli et al. 1989). The spectra of SN 1998bw were vertically displaced for presentation purposes. [*See the electronic edition of the Journal for a color version of this figure.*]

the first and second night after the GRB. This is confirmed by PSF-matched image subtraction. We believe that we have seen the NIR afterglow of GRB 031203. The magnitudes are $J = 20.60 \pm 0.09$, $H = 19.05 \pm 0.07$, and $K = 17.56 \pm 0.05$ (9 hr after the GRB), obtained by subtracting the host contribution. Cobb et al. (2004) have *I*-band observations at similar epochs, and they do not report evidence of variability. However, extrapolation to the visible region yields $I \sim 23.4$, quite a faint value when compared to the host luminosity $I \approx 19.4$. Little contribution from the afterglow is seen in our measurement of December 5, implying a quick decay between the two nights [$F(t) \propto t^{-\alpha}$, with $\alpha \gtrsim 2$]. However, there is no variation between the two *K*-band observations of the first night (separated by 2.6 hr), suggesting a break in the light curve or a bumpy behavior. In Figure 2, we compare the spectrum in the NIR and X-ray regions (Watson et al. 2004). A discontinuity is apparent, indicating a different origin for the emission in the two bands. The X-ray component has a much harder spectrum and a slower decay ($\alpha = 0.55 \pm 0.05$). Interestingly, Watson et al. (2004) infer a fast decay of the early-time X-ray afterglow, consistent with our NIR value ($\alpha \gtrsim 1.7$). In the standard model of afterglows (e.g., Sari et al. 1998), a fast decay is consistent with a soft spectrum blueward of the peak frequency.

A few days after the GRB, a rebrightening is apparent in all optical/NIR bands. The rebrightening amounts to ≈30% of the total flux and is coincident with the center of the host galaxy to within 0″.1 (≈200 pc at $z = 0.1055$). For comparison, we show in Figure 1 the *VRI* light curves of SN 1998bw (Galama et al. 1998; McKenzie & Schaefer 1999), placed at $z = 0.1055$ and dereddened with $E_{B-V} = 1.1$ (see below). Interpolation of the *UBVRI* data was performed in order to estimate the fluxes of SN 1998bw at the frequencies corresponding to the observed bands. Even after correcting for cosmological time dilation, the light curve of SN 2003lw is broader than that of SN 1998bw and requires an additional stretching factor of ≈0.9 to match the *R* and *I* bands. Near the peak, the light curve is rather flat, resembling the hypernova SN 1997ef (Iwamoto et al. 2000) more than SN 1998bw. The *R*-band maximum is reached on approximately 2003 December 24 (∼18 comoving days after the GRB). We note that the details of the light-curve shape are sensitive to the removal of the host contribution. This may explain the different finding of Cobb et al. (2004), who find a longer rise, and Thomsen et al. (2004), who need no stretch. Assuming a light-curve shape similar to SN 1998bw, which had a rise time of 16 days in the *V* band, our data suggest an explosion time nearly simultaneous with the GRB. However, given that SN 2003lw was not strictly identical to SN 1998bw, and as we lack optical data in the days immediately following the GRB, a lag of a few days cannot be ruled out. Type Ic SNe usually reach *V*-band maximum in ∼12–20 days, the brightest events showing a slower evolution (see, e.g., Fig. 2 of Mazzali et al. 2002).

A precise determination of the absolute magnitude of the SN is made difficult by the uncertain, and significant, extinction. C04 and Prochaska et al. (2004) constrain the average combined Galactic and host extinction to be $E_{B-V} \approx 1.1$ based on the Balmer ratios of the host galaxy. Given the good spatial coincidence of the SN with the center of the host, such a value is likely a good estimate for the SN extinction. We also adopt a Galactic extinction law (Cardelli et al. 1989) with $R_V = 3.1$. With the assumed reddening, SN 2003lw appears brighter than SN 1998bw by 0.5 mag in the *V*, *R*, and *I* bands. The absolute magnitudes of SN 2003lw are hence $M_V = -19.75 \pm 0.15$, $M_R = -19.9 \pm 0.08$, and $M_I = -19.80 \pm 0.12$. Thomsen et al. (2004), using *I*-band data, also found that SN 2003lw was brighter than SN 1998bw by ∼0.55 mag, in full agreement with our result. Cobb et al. (2004), however, found a comparable luminosity for the two SNe; this discrepancy is entirely due to the lower extinction they assume.

Figure 3 shows the spectra of the rebrightening on 2003 December 20 and 30 (14 and 23 rest-frame days after the GRB, respectively), after subtracting the spectrum taken on 2004 March 1 (81 rest-frame days after the GRB). This assumes that the latter spectrum contains only a negligible contribution from the SN, which is confirmed by the photometry (Fig. 1). The spectra of SN 2003lw are remarkably similar to those of SN 1998bw obtained at comparable epochs (shown as dotted lines in Fig. 3; from Patat et al. 2001). Both SNe show very broad absorption features, indicating large expansion velocities. Thus, we tentatively classify SN 2003lw as a hypernova. The main absorptions are identified in Figure 3 as in SN 1998bw, following Iwamoto et al. (1998). The velocity of the Si II line in SN 2003lw is apparently smaller than in SN 1998bw. The broad peaks near 5300 and 6600 Å are probably the emission components of P Cygni profiles due to the blending of several lines. There is evolution between the two epochs: the bluer bump is observed at longer wavelengths in the second spectrum and is slightly narrower. Moreover, the shape of the redder peak is different in the two epochs. Both peaks appear at redder wavelengths than in SN 1998bw. Detailed modeling of the spectra will be presented elsewhere (P. A. Mazzali et al. 2004, in preparation).

By modeling the X-ray dust echo, Watson et al. (2004) concluded that GRB 031203 was an X-ray flash (XRF); however, the prompt emission data do not confirm this hypothesis (S. Sazonov et al. 2004, in preparation). This event, like GRB 980425 (Pian et al. 2000), seems therefore to violate the correlation between the isotropic-equivalent gamma-ray energy $E_{\rm iso}$ and the peak spectral energy E_p (Amati et al. 2002; Lamb et al. 2003). In fact, assuming $E_{\rm iso} \sim 1.5 \times 10^{50}$ ergs (1–10,000 keV; Watson et al. 2004), the Amati et al. (2002) relation would imply $E_p \sim 10$ keV, a value indicating an XRF nature for GRB 031203. This is in contrast with *INTEGRAL* data. Of course, this issue will be settled only after a thorough analysis of the prompt emission spectra.

The afterglow of GRB 031203 was very weak, the faintest ever detected in the optical/NIR. Extrapolation in the R band yields a luminosity ∼200 times fainter than the dimmest afterglow discovered so far (GRB 021211; Fox et al. 2003; Pandey et al. 2003). The detection of the SN optical light implies that an extreme dust obscuration was not the reason for such faintness. Given also the low redshift of the event, this example shows that some optical afterglows may escape detection just because they are faint (e.g., Fynbo et al. 2001; Lazzati et al. 2002; De Pasquale et al. 2003).

GRB 031203, together with GRB 980425 at $z = 0.085$, were very dim events, perhaps jets observed far from their axes (e.g., Maeda et al. 2002; Yamazaki et al. 2003). Being so faint, they would have been likely missed at cosmological distances. Since the volume they sample is much smaller than that probed by classical, distant GRBs with $\langle z \rangle \approx 1$, the rate of these events could be much larger. As noted by Thomsen et al. (2004), this would increase the detection rate for the *Swift* satellite (Gehrels et al. 2004). More rapid and efficient observations, also soon feasible thanks to *Swift*, will allow one to make a detailed study of this largely unexplored class of events.

GRB 031203 was quite similar to GRB 980425, even if overall more powerful. Both events consisted in a single, underenergetic pulse. Their afterglows were very faint or absent in the optical and showed a very slow decline in the X-ray (Pian et al. 2000; Watson et al. 2004). Finally, they were both accompanied by a powerful hypernova.

The data presented in this work were obtained with ESO telescopes under programmes 072.D-0480 and 072.D-0137. We are grateful to the ESO staff and in particular to M. Billeres, O. Hainaut, S. Hubrig, R. Johnson, C. Lidman, G. Marconi, and T. Szeifert. F. Patat is warmly acknowledged for providing the SN 1998bw data. D. M. thanks L. Ballo for useful discussions. This work was supported by contract ASI/I/R/390/02 of the Italian Space Agency for the Italian *Swift* Project, by the Italian Ministry for University and Research, and by the Italian National Institute for Astrophysics (INAF). We thank the anonymous referee for useful suggestions and a prompt reply.

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