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

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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 $\sim 9$ 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 980419 (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 considered as hypernovae (e.g., Iwamoto et al. 1998). Finally, bumps in the light curves of several afterglows, peaking $\sim 20$ 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 021121 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 $\sim 30$ s and a peak flux of $1.3 \times 10^{-7}$ erg 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, $E_{\text{iso}} \sim 3 \times 10^{49}$ 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. 2004).
2. OBSERVATIONS AND DATA REDUCTION

Photometry.—We observed the field of GRB 031203 \( \approx 7 \) 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.

Additional \( K \) and \( I \) photometry was acquired with the 2 m Multicolor Active Galactic Nuclei Monitoring (MAGNUM) telescope of the University of Tokyo (Yoshi 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 H\(\alpha \) 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 \( \approx 10 \) \( \AA \)) 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

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**Table 1: Summary of Photometric Observations**

| UT Start       | Seeing (arcsec) | Instrument | Band | Magnitude* |
|----------------|-----------------|------------|------|------------|
| 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 |
| 2004 Dec 15.514 | 0.6             | FORS1      | R    | 20.14 ± 0.03  |
| 2005 Dec 17.284 | 0.7             | FORS1      | R    | -0.009 ± 0.016 |
| 2005 Dec 23.295 | 0.5             | FORS1      | R    | -0.060 ± 0.016 |
| 2005 Dec 28.296 | 0.6             | FORS1      | R    | -0.051 ± 0.010 |
| 2005 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 29.197 | 0.9             | 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 |
| 2004 Dec 25.503 | 1.1             | MAGNUM     | K    | 16.61 ± 0.04 |
| 2004 Jan 06.445 | 1.1             | MAGNUM     | K    | 16.58 ± 0.04 |

* Magnitudes are given relative to the boldface epoch.
However, there is no variation between the two nights, implying a quick decay between the two nights. Contribution from the afterglow is seen in our measurement of epochs, and they do not report evidence of variability. However, Cobb et al. (2004) have found cm/
11002 from our data by subtracting the host contribution and assuming .

The X-ray spectrum is from Watson et al. (2004; reported at t = 9 hr using the X-ray decay slope), who find N_h = 8.8 × 10^15 cm^{-2} and β_h = 0.90 ± 0.05. [See the electronic edition of the Journal for a color version of this figure.]

Figure 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_{p-V} = 1.1. The NIR spectral index is β = 2.36 ± 0.02 (F ∝ r^{-β}). The X-ray spectrum is from Cobb et al. (2004: reported at t = 9 hr using the X-ray decay slope), who find N_h = 8.8 × 10^15 cm^{-2} and β_h = 0.90 ± 0.05. [See the electronic edition of the Journal for a color version of this figure.]

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_{p-V} ≈ 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 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 ± 0.15, M_R = −19.9 ± 0.08, and M_I = −19.80 ± 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 (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_{p-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.]

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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 \( E_{\gamma} \) and the peak spectral energy \( E_{\text{p}} \) (Amati et al. 2002; Lamb et al. 2003). In fact, assuming \( E_{\text{p}} \sim 1.5 \times 10^{50} \) ergs (1–10,000 keV; Watson et al. 2004), the Amati et al. (2002) relation would imply \( E_{\gamma} \sim 10 \) keV, a value indicating an XRF nature for GRB 031203. This is in contrast with \textit{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; Pan-dey 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 \( (z) \approx 1 \), the rate of these events could be much larger. As noted by Thomsen et al. (2004), this would increase the detection rate for the \textit{Swift} satellite (Gehrels et al. 2004). More rapid and efficient observations, also soon feasible thanks to \textit{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.

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