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Letter to the Editor

# The supernova 2003lw associated with X-ray flash 031203★,★★

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**Abstract.** The X-Ray Flash (XRF), 031203 with a host galaxy at $z = 0.1055$, is, apart from GRB 980425, the closest $\gamma$-Ray Burst (GRB) or XRF known to date. We have monitored its host galaxy from 1–100 days after the burst. In spite of the high extinction to the source and the bright host, a significant increase and subsequent decrease has been detected in the apparent brightness of the host, peaking between 10 and 33 days after the GRB. The only convincing explanation is a supernova (SN) associated with the XRF, SN2003lw. This is the earliest time at which a SN signal is clearly discernible in a GRB/XRF (apart from SN1998bw). SN2003lw is extremely luminous with a broad peak and can be approximately represented by the lightcurve of SN1998bw brightened by ∼0.55 mag, implying a hypernova, as observed in most GRB-SNe. The XRF–SN association firmly links XRFs with the deaths of massive stars and further strengthens their connection with GRBs. The fact that SNe are also associated with XRFs implies that *Swift* may detect a significant population of intermediate redshift SNe very soon after the SN explosions, a sample ideally suited for detailed studies of early SN physics.

**Key words.** gamma rays: bursts – supernovae: general

## 1. Introduction

It is now firmly established that at least some long-duration $\gamma$-ray bursts (GRBs) are accompanied by the contemporaneous explosion of a supernova (SN, e.g. Hjorth et al. 2003b; Stanek et al. 2003; Della Valle et al. 2003; Galama et al. 1998), consistent with expectations for some models of GRBs involving the collapse of massive stars (MacFadyen et al. 2001; MacFadyen & Woosley 1999). The lack of large numbers of SN–GRB associations may be explained, at least in part, by the difficulty of obtaining the optical spectra of SNe with redshifts usually greater than unity, against the combined backgrounds of the fading afterglow and the host galaxy.

X-Ray Flashes (XRFs), a class of very soft bursts, was discovered with *BeppoSAX* (Heise et al. 2001). They are intense, short-lived flashes of soft X-rays of extragalactic origin (Bloom et al. 2003; Soderberg et al. 2003; Prochaska et al. 2004), and may be defined by a larger X-ray than $\gamma$-ray fluence in the burst ($S_X/S_\gamma > 1$, Lamb et al. 2003). The similarity in the durations of XRFs and GRBs (Heise et al. 2001; Barraud et al. 2003), the continuum of spectral properties observed between the two classes (Lamb et al. 2003), their cosmological origins in each case (Bloom et al. 2003; Soderberg et al. 2003), and the similarity of their optical and X-ray afterglows (Fynbo et al. 2004; Watson et al. 2004), makes it seem probable that XRFs and GRBs have a similar origin. While GRBs and XRFs are located at cosmological distances, few have been located at redshifts <0.3. They are: GRB 030329 at $z = 0.1685$ (associated with SN2003dh, Hjorth et al. 2003b; Stanek et al. 2003), XRF 020903 with its probable host galaxy at $z = 0.251$ (Soderberg et al. 2003), GRB 980425 probably associated with SN1998bw at $z = 0.0085$ (Galama et al. 1998) and recently, the XRF referred to as GRB 031203 at $z = 0.1055$ (Watson et al. 2004; Prochaska et al. 2004). Of these, XRF 020903 had a very low peak spectral energy and a low luminosity

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(Sakamoto et al. 2004; Soderberg et al. 2003) and GRB 980425 had an extraordinarily low luminosity (Kulkarni et al. 1998). That GRB 031203 was in fact an XRF was discovered because of the detection of a transient, outwardly moving ring of X-ray emission surrounding the afterglow (Vaughan et al. 2004). This was interpreted as reflection of the original burst event and early afterglow off dust sheets in the Galaxy, from which strong lower limits on the prompt soft X-ray fluence were obtained (Watson et al. 2004).

The high extinction toward GRB 031203 ($E(B-V) \approx 1$, Schlegel et al. 1998; Prochaska et al. 2004), though instrumental in allowing the detection of the dust reflection halo, also hampered attempts to follow the afterglow at optical wavelengths and no optical or infrared afterglow was detected. The location of the burst is therefore determined from X-ray and radio detections. Both of these locate GRB 031203 unambiguously on a sub-luminous, blue, and strongly star-forming galaxy at fairly low redshift ($z = 0.1055$, Prochaska et al. 2004), where the probability of a chance association with such a galaxy is not very significant (Watson et al. 2004; Prochaska et al. 2004).

Strong evidence for the association of XRFs with the deaths of massive stars was present in the lightcurve of XRF 030723 (Fynbo et al. 2004), but the analysis of that burst was complicated by the lack of a redshift. Because of the low redshift there was considerable interest in attempting to discover a SN associated with GRB 031203, in particular since it has been found to be an XRF and the host galaxy was therefore monitored independently by a number of groups in order to find the photometric variability that would indicate a SN (e.g. this paper; Bersier et al. 2004; Tagliaferri et al. 2004b; Cobb et al. 2004; Gal-Yam et al. 2004). This would be the first SN associated with an XRF with a spectroscopic redshift, firmly establishing the association of XRFs with the deaths of massive stars and confirming the suspected link between XRFs and GRBs.

In Sect. 2 we describe *I*-band imaging observations of the host galaxy of GRB 031203 (HG 031203) over the first 100 days since the burst, and in Sects. 3 and 4 the discovery of a SN (named SN2003lw, Tagliaferri et al. 2004a) associated with the XRF and the implications of this discovery. This paper supersedes an earlier preliminary report on some of these observations (Hjorth et al. 2003a).

A cosmology where $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$ is assumed throughout.

## 2. Observations and data reduction

HG 031203 was observed in the *I*-band with the DFOSC instrument in imaging mode (0.396 arcsec/pixel) on the Danish 1.5 m telescope, La Silla, and with StanCam (0.176 arcsec/pixel) on the 2.56 m Nordic Optical Telescope, La Palma.

The main obstacle to obtaining accurate photometry was strong reflection of the light from a very bright star off optical surfaces in the camera lens (this was the cause of the early report of a flat lightcurve in Hjorth et al. 2003a). The telescope pointing was changed between exposures in the usual way in order to eliminate the influence of pixel defects by taking the median of the sky-aligned images. This, however, is not the best way to proceed when dealing with large reflections. Instead, we decided to do straight aperture photometry on the individual images that were free of reflections near the host galaxy. Flat field exposures were obtained of the twilight sky for each night and bias subtraction and flat-fielding were done in the standard way.

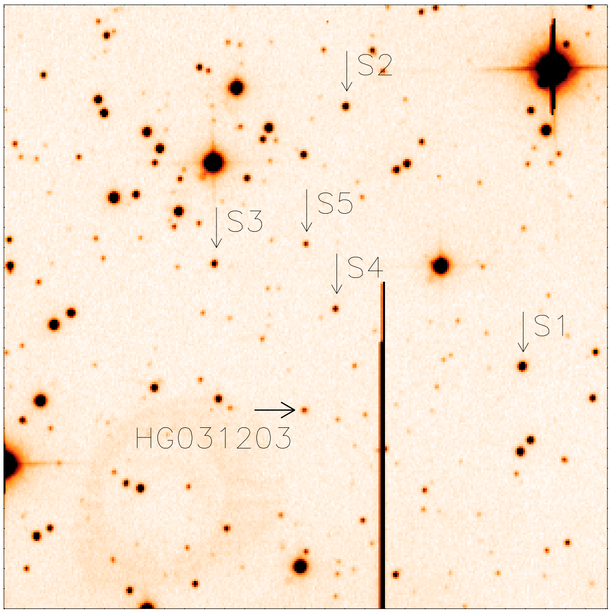


**Fig. 1.** *I*-band image of the field of HG 031203. North is up, east to the left; the image is 2′ on a side. The positions of the host galaxy and of the comparison stars are noted. Blooming from a bright star, (outside this image) is visible as a N-S streak and a ring caused by reflection is evident just to the southeast of HG 031203.

An isolated comparison star (S1), 2.5 mag brighter than HG 031203, and four fainter stars (S2–S5) in the vicinity of the host, were chosen to evaluate the precision of our aperture photometry (Fig. 1). Photometry was carried out using the `DAOPHOT` package supplemented by `daomatch` and `daomaster` kindly supplied by Peter Stetson (priv. comm.), and used an aperture of 1.98″ radius, while the sky level was estimated using an annular aperture with inner and outer radii of 3.96″ and 5.94″ respectively. The full width at half maximum (*FWHM*) of the seeing was 0.9–1.1″.

Weighted average instrumental magnitudes were calculated for each night using weights based on the standard errors supplied by the aperture photometry routine in the `DAOPHOT` package; these errors are based on photon and read noise only. The instrumental magnitudes obtained with StanCam were colour corrected to the DFOSC instrumental magnitudes by demanding identical relative photometry derived from nearly simultaneous exposures obtained by StanCam and DFOSC. This colour-correction was 0.13 mag in the case of HG 031203.

The photometry of stars S2–S5 and the host galaxy, relative to the comparison star S1, is given in Table 1. The standard error for the magnitude difference is also given, assuming photon and read noise only. As the pointing was changed between exposures, we can expect some flat-fielding errors independent of magnitude; the principle uncertainty is, however, related to the

**Table 1.** Comparative photometry relative to the star S1. Relative photometric uncertainties in the last significant digit are listed in parentheses after their respective values. The last column gives the reduced $\chi^2$ of the fit to a constant flux value. Seeing corresponds to the full width at half-maximum of point sources in the image. The data were obtained with DFOSC on the Danish 1.5 m telescope except that marked with a †, where StanCam on the NOT was used.

| | Days since XRF (3.92 Dec. 2003, UT) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1.36 | 2.29 | 6.43 | 8.28 | 9.33 | 32.19† | 45.34 | 63.45 | 100.12 | |
| Exp. (s): | 4 × 600 | 3 × 600 | 3 × 600 | 5 × 420 | 3 × 600 | 6 × 300 | 5 × 600 | 4 × 600 | 5 × 600 | |
| Seeing: | 1.09″ | 1.03″ | 0.95″ | 0.87″ | 0.85″ | 0.83″ | 0.98″ | 1.05″ | 1.00″ | |
| Object | Relative photometry | | | | | | | | | $\chi^2_\nu$ |
| S2 | 1.000(5) | 0.997(5) | 1.013(6) | 1.009(4) | 1.004(5) | 0.994(7) | 1.004(3) | 1.01(1) | 0.992(5) | 1.71 |
| S3 | 1.396(6) | 1.386(7) | 1.388(8) | 1.378(6) | 1.378(6) | 1.390(9) | 1.407(4) | 1.42(1) | 1.391(6) | 3.29 |
| S4 | 1.923(9) | 1.96(1) | 1.92(1) | 1.921(8) | 1.93(1) | 1.94(1) | 1.929(6) | 1.91(2) | 1.90(1) | 3.15 |
| S5 | 2.36(1) | 2.37(2) | 2.41(2) | 2.39(1) | 2.39(1) | 2.35(2) | 2.371(9) | 2.37(3) | 2.40(2) | 1.50 |
| HG 031203 | 2.47(1) | 2.48(2) | 2.37(2) | 2.38(1) | 2.34(1) | 2.33(2) | 2.41(1) | 2.52(4) | 2.49(2) | 15.26 |

influence of reflections from the bright star – such additional background errors are expected to be larger for fainter stars. In addition to the bright ring-shaped reflections the sky background appears somewhat non-uniform (Fig. 1), but it is difficult to judge if this non-uniformity is due to scattered light or flat-fielding errors. The variability of the four stars and the host galaxy is tested by calculating the $\chi^2$ per degree of freedom (d.o.f., $\chi^2_\nu = \chi^2$/d.o.f.) for a constant flux fit, which is also given in Table 1. The fact that for the comparison stars, $\chi^2_\nu \geq 1.5$, suggests that other sources of error must remain in addition to the photon noise. These are probably caused by a combination of small scale background variations and unavoidable flat-fielding errors. Judging from the standard errors and the $\chi^2_\nu$ values given in Table 1, the combined errors could hardly exceed 0.02 mag. The very high value of $\chi^2_\nu$ for the host galaxy strongly suggests the existence of an intrinsically variable source superposed on the galaxy.

The zeropoint used for the absolute photometry was tied to that of Cobb et al. (2004).

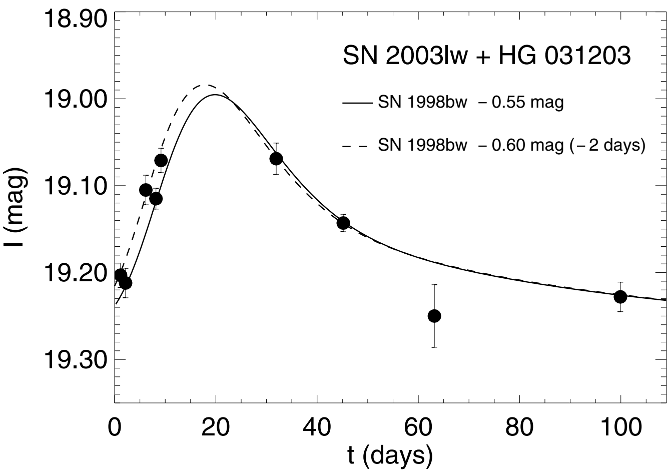


**Fig. 2.** The $I$-band lightcurve of HG 031203 (uncorrected for extinction). The characteristic supernova "bump" is apparent. The reddened ($A_I$ = 2.14 mag) and scaled (−0.55 mag) intrinsic lightcurve of SN1998bw, with the flux of the galaxy ($I_{\rm host}$ = 19.27) added, is plotted for comparison, starting at the time of the XRF (solid line) and starting two days prior to the XRF (scaled by −0.6 mag, dashed line). The brightened SN1998bw lightcurve is quite an accurate template for the data.

## 3. Results

The lightcurve of HG 031203 is clearly variable and rises and then falls in a manner characteristic of a SN superimposed on a host galaxy (Fig. 2). While it is possible that the first two datapoints may be related to the afterglow of the XRF, it is clear from the shape and timing of the bump that there was a SN (2003lw) in HG 031203 contemporaneous with the XRF. This is the first SN associated with an XRF (with known redshift, see Fynbo et al. 2004). In Fig. 2 we plot SN1998bw as it would appear in HG 031203 (assuming $I_{\rm host}$ = 19.27 mag) and it gives a reasonable approximation to the lightcurve if we allow it to be brighter by 0.55 mag. However, if SN2003lw and GRB 031203 were simultaneous, the rise appears marginally faster than SN1998bw; alternatively, placing the start of SN1998bw template up to two days prior to the XRF is consistent with the observations (Fig. 2). It is already apparent from the lightcurves of SNe associated with GRBs/XRFs (011121, 021211, 030329, 030723), that SN1998bw is not a universal template, with some being faster (2003dh, Hjorth et al. 2003b) or having an early peak in the near-infrared, and fading more quickly e.g. 2001ke (Garnavich et al. 2003) or XRF 030723 (Fynbo et al. 2004). Given the variation in GRB-associated SN lightcurves, it is slightly surprising that SN2003lw follows the brightened SN1998bw template fairly well.

Whether SN2003lw is intrinsically brighter than SN1998bw, depends entirely on the extinction to the SNe. Using the values measured from the Balmer decrement, Prochaska et al. (2004) found the total $E(B-V)$ = 1.17 ± 0.1, (somewhat higher than, but consistent with, the values obtained from Galactic dust-maps ($E(B-V)$ = 1.04, Schlegel et al. 1998), with $R_V$ = 3.1 (Cardelli et al. 1989) giving a good fit to the ratio of Balmer line fluxes (Prochaska et al. 2004). Therefore, the total $I$-band extinction toward HG031203 is $A_I$ = 2.14 ± 0.2 mag and is the value used here.

This means that SN2003lw is likely to have been ∼0.55 mag brighter at peak than SN1998bw. Since we use a very high value for the total extinction toward SN1998bw, $A_I = 0.12$[1], this estimate may be slightly low. It seems unlikely that the total extinction to SN2003lw is much less than $A_I = 1.4$ mag, a value $>3\,\sigma$ lower than that measured using the Balmer line ratios mentioned above and consistent with the lowest estimate of Galactic extinction in this direction (Prochaska et al. 2004, and references therein). Using these limits, SN2003lw must therefore have been at least as bright as SN1998bw. This implies a high mass of $^{56}$Ni produced in the explosion (Iwamoto et al. 1998), and together with the similarity with the lightcurve of SN1998bw, suggests that SN2003lw was a hypernova.

The existence of SN2003lw in HG 031203, suspected soon after the GRB (Bailyn et al. 2003) and suggested again much later (Bersier et al. 2004), also now appears to have been confirmed spectroscopically (Tagliaferri et al. 2004b). Our results appear consistent with those preliminary reports. Recently Cobb et al. (2004) with more extensive temporal coverage but larger photometric uncertainties than reported here, suggest that the fast rise (Fig. 2) noted above and a broader peak implies a later maximum than we have inferred.

## 4. Discussion

The SN associated with GRB 031203 is a confirmation of an expectation that XRFs and GRBs are essentially two ends of the continuum of cosmic high-energy bursts (e.g., Amati et al. 2002; Sakamoto et al. 2004; Watson et al. 2004) that result from the destruction of massive stars. It has been posited that the lower apparent luminosities and lower peak energies of XRFs may both be related to the fact that these bursts are viewed at larger off-axis angles than GRBs (Granot et al. 2002; Yamazaki et al. 2002, 2004; Zhang et al. 2003). XRFs are typically found at lower redshifts than GRBs, probably because of their lower overall luminosities (Amati et al. 2002; Atteia 2003; Yamazaki et al. 2002). Since there is no obvious reason to expect that the SNe associated with XRFs are less luminous optically than the SNe associated with GRBs, it seems likely that proportionally more XRF-SNe than GRB-SNe will be found if the limiting factor to discovering GRB/XRF-SNe is simply the very large distances involved.

Now that the association with SNe is secure, the question arises of what the general characteristics of GRB-SNe are. The fact that the absolute magnitudes of the SNe of GRB 980425, 011121, 021211, 030329 and now 031203 are all within a magnitude of each other (the SN associated with 021211 being the faintest and 031203 the brightest), centred near $M_B \sim -19.5$ mag (Galama et al. 1998; Bloom et al. 2002; Garnavich et al. 2003; Della Valle et al. 2003; Hjorth et al. 2003b; Lipkin et al. 2003) when the mean $M_B$ of Type Ib/c SNe (the SN type of SN1998bw/GRB 980425 and 2003dh/GRB 030329, Patat & Piemonte 1998; Mazzali et al. 2003; Matheson et al. 2003) is −17.12 mag, with a standard deviation in the magnitudes of 0.74 (Richardson et al. 2002; Miller & Branch 1990) is intriguing. The fact that there is some evidence for a bimodal distribution in the absolute magnitudes of Type I b/c SNe (Richardson et al. 2002; Miller & Branch 1990) with mean $M_B = -19.77$ mag and standard deviation of 0.33 for the brighter group merely heightens the interest. For the moment the statistics are not good enough to go beyond the statement that it is possible that only the brightest SNe can be observed above the afterglow and galaxy light, and therefore we sample the high end of the population preferentially. However, it does not seem unreasonable to suggest that such a bimodal distribution may indeed exist in SNe Ib/c and that this more luminous population subset is associated with GRBs, or with the specific population of stars that produce GRBs.

GRB 031203 was a relatively faint *Integral* burst with a peak flux of only $1.3 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ (Mereghetti & Gotz 2003). In terms of peak $\gamma$-ray luminosity, GRB 031203 is one of the faintest localised so far. The *Swift* satellite, with its high $\gamma$-ray sensitivity and large field of view, should detect many more faint GRBs than previous missions. While some of these will be at high redshift, there should be a significant population of intrinsically faint XRFs (and GRBs) at modest redshift, similar to GRB 031203, that will also be detected. These will provide excellent targets to study the earliest phases in the evolution of Type Ib/c SNe from minutes to months after the burst, especially considering that most of these, contrary to GRB 031203, will be relatively unextincted (had GRB 031203 not been close to the plane of the Galaxy, the SN peak magnitude would have been $m_V \sim 19$ mag). In this way *Swift* may unintendedly open an entirely new research field within SN physics, allowing extremely early access to, and a substantial increase in the rate of detections of type Ib/c SNe.

## 5. Conclusions

We have monitored the host galaxy of the XRF, GRB 031203 in the near-infrared, from 1–100 days following the burst. In spite of the bright host galaxy and high extinction, we have discovered positive evidence of a SN, peaking ∼20 days after the XRF and can clearly trace the early SN rise. At $z = 0.1055$, this is the closest GRB/XRF-associated SN discovered so far, after SN1998bw, and the first SN associated with an XRF with known redshift. This confirms the strong case for an association between XRFs and SNe found in XRF 030723 (Fynbo et al. 2004). The SN appears to have a somewhat higher peak luminosity than observed in SN1998bw, but the lightcurve is otherwise fairly similar, implying that the SN accompanying GRB 031203 was a hypernova. It is likely that *Swift* will detect a significant population of faint bursts like GRB 031203 and hence allow the study of (type Ib/c) core-collapse SN at much earlier times than what has been possible so far; this may have a substantial impact on SN research.

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[1] This is in fact an upper limit to the extinction in SN1998bw, based on the non-detection Na I D lines in high-resolution spectra (Patat et al. 2001).

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