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THE SUPERNOVA ASSOCIATED WITH GRB 031203: SMARTS OPTICAL-INFRARED LIGHT CURVES FROM 0.2 TO 92 DAYS

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ABSTRACT

Optical and infrared monitoring of the afterglow site of gamma-ray burst GRB 031203 has revealed a brightening source embedded in the host galaxy, which we attribute to the presence of a supernova (SN) related to the GRB ("SN 2003lw"). We present details of the discovery and evolution of SN 2003lw from 0.2 to 92 days after the GRB, derived from SMARTS consortium photometry in *I* and *J* bands. GRB 031203 was an intrinsically faint GRB, and the optical light curve is dominated by the SN after the first few days. A template Type Ic light curve, constructed from SN 1998bw photometry, is consistent with the peak brightness of SN 2003lw, although the light curves are not identical. Differential astrometry reveals that the SN, and hence the GRB, occurred less than 300 h_{71}^{-1} pc (3 σ) from the apparent galaxy center.

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

On-line material: machine-readable table

1. INTRODUCTION

Since the discovery of gamma-ray burst (GRB) afterglows, the evidence for a physical connection between GRBs and core-collapse supernovae (SNe) has mounted (see reviews by van Paradijs 1999 and Mészáros 2001). Particularly compelling were observations of light curves and broadband photometry of SN-like features embedded in GRB afterglow light (see Bloom 2003). Recently, spectroscopic evidence (Stanek et al. 2003; Hjorth et al. 2003; Kawabata et al. 2003) confirmed that GRBs are produced in the death of massive stars (Woosley 1993). To date, SN signatures have been reliably found in only a few GRBs (see Bloom 2003), necessitating the search for and the study of new GRB-related SNe.

GRB 031203 triggered the IBIS instrument on board the *I NTEGRAL* (*INTErnational Gamma-Ray Astrophysics Laboratory*) satellite on 2003 December 3 at 22:01:28 UT (Gotz et al. 2003), leading to quick discoveries of X-ray (Campana et al. 2003) and radio afterglows (Frail 2003; Soderberg et al. 2003). Spectroscopy of the host galaxy coincident with the radio transient yielded a redshift of $z = 0.1055$ (Prochaska et al. 2004), likely the redshift of the burst itself. The low redshift (second only to the unusual GRB 980425) of GRB 031203 presents a rare opportunity to create a well-sampled SN light curve using modest aperture telescopes. We began our observations of the field 5 hr after trigger and continued frequent monitoring for several months. We reported our discovery of an increase in brightness of the aperture magnitude of the host and first suggested the emergence of a supernova was responsible (Bailyn et al. 2003). Monitoring of the SN by other groups has now confirmed its presence both photometrically (Bersier et al. 2004) and spectroscopically (Tagliaferri et al. 2004a), and the SN has been designated SN 2003lw (Tagliaferri et al. 2004b). Other sources of transient emission, such as AGN activity, are ruled out by the spectroscopic evidence that the transient source is associated with an SN.

In this Letter, we present optical and infrared data obtained with the SMARTS 1.3 m telescope and ANDICAM instrument between 0.2 and 92 days after the detection of GRB 031203. Observations and data reduction are reported in § 2. In § 3, we describe the aperture photometry and image subtraction carried out on these data. The resultant evidence of an SN associated with GRB 031203 is presented. A comparison between this SN and SN 1998bw is made in § 4.

2. OBSERVATIONS AND DATA REDUCTION

Observations commenced on 2003 December 4 at 3:00 UT, approximately 5 hrs after the *INTEGRAL* detection of the long-duration (20 s) GRB 031203 (Gotz et al. 2003), and follow-up imaging continued for the next 3 months. Data were obtained using the ANDICAM (A Novel Dual Imaging CAMera) instrument mounted on the 1.3 m telescope at Cerro Tololo Inter-American Observatory.[4] This telescope is operated as part of the Small and Moderate Aperture Research Telescope System (SMARTS) consortium.[5] The ANDICAM detector consists of a dual-channel camera that allows for simultaneous optical and IR imaging. The Fairchild 447 2048 × 2048 optical CCD has a 6′.3 × 6′.3 field of view, while the Rockwell 1024 × 1024 HgCdTe Astronomical Wide Area Infrared array has a 2′.4 × 2′.4 field of view. Both optical and IR images are double-binned in software to give an optical pixel scale of 0″.27 pixel^{-1} and an IR pixel scale of 0″.37 pixel^{-1}. While standard optical integrations are underway, the ANDICAM instrument allows IR images to be "dithered" by the slight adjustment of three tilt axes of an internal mirror.

As GRB 031203 was at low Galactic latitude and thus subject to high extinction, only *I*-band data were obtained in the optical. *J*-band data were obtained simultaneously. A combination of seven telescope repoints and five internal dithers were used to obtain seven separate 360 s *I*-band images and 35 separate 60 s *J*-band images per data set. Standard reduction was performed on the *I*-band images, including overscan bias subtraction, zero subtraction, and flat-fielding. The seven *I*-band images were then aligned and averaged to produce a single master *I*-band frame.

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[4] See http://www.astronomy.ohio-state.edu/ANDICAM.

[5] See http://www.astro.yale.edu/smarts.

TABLE 1
GRB 031203/SN 2003lw Host Galaxy Photometry

Days after GRB[a]	*I* Magnitude[b]	*J* Magnitude[b]
0.21	19.12 ± 0.03	...
0.26	19.19 ± 0.03	...
0.29	19.23 ± 0.03	...
0.31	19.17 ± 0.03	...
1.31	19.22 ± 0.03	...
2.31	19.15 ± 0.03	18.28 ± 0.06
3.33	19.22 ± 0.03	18.38 ± 0.06

Note.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.
[a] Days after burst trigger at 2003 December 3, UT 22:01:28.
[b] There is an additional uncertainty of 0.07 mag in the transformation of relative to apparent magnitudes.

IR flats were taken at two different sky brightnesses. Flats with a "bright" sky level were median-combined to produce a bright flat frame, and flats with a "dim" sky level were median-combined to produce a dim flat frame. The master flat field was produced by subtracting the dim flat frame from the bright flat frame. Each *J*-band image was divided by the normalized master flat field. Five sky frames were then produced, one for each dither position. Each sky frame was formed by median-combining sets of seven images taken at a given dither position. Median combining produced star-free sky frames since each of the seven images at that dither position were taken at a slightly different telescope position. Corresponding sky frames were subtracted from each image with rescaling to compensate for changes in brightness. Finally, all 35 sky-subtracted images were aligned and averaged to produce a single master *J*-band frame for that epoch.

3. DATA ANALYSIS

The discovery of SN 2003lw was made noting a differential brightening in the aperture magnitude about the apparent host from day 0.2 to day 8.3 (Bailyn et al. 2003). We have analyzed the full data set using both aperture photometry and image-subtraction photometry and find that both methods give consistent results for the SN light curve. As image subtraction introduces an extra source of error, we chose to focus our attention on the aperture photometry results.

3.1. *Aperture Photometry*

Seeing-matched aperture photometry of the host galaxy of GRB 031203 (Prochaska et al. 2004) was performed. The seeing was matched to an FWHM of $\sim 1''.2$. The relative magnitude of the host was determined by comparison with 12 on-chip, nonvariable, "standard" objects. The aperture radius used was $1''.9$ in *I* and $2''.6$ in *J* and was chosen to enclose all light from the galaxy significantly above the sky background level. Relative magnitudes were converted to apparent magnitudes by comparison, on photometric nights, with the eight Landolt standard stars in the field of Rubin 149 (Landolt 1992) for the *I*-band images and with the Persson IR standard stars T832-38078, LHS 2397a, P9106, and P9150 (Persson et al. 1998) for the *J*-band images.

The photometric data are summarized in Table 1, and the resultant light curves are shown in Figure 1. Both light curves clearly reveal the rise and then decay of a supernova, with a peak between 26 and 34 days. The apparent magnitude of the host galaxy without the SN component is 19.21 ± 0.01 in *I*

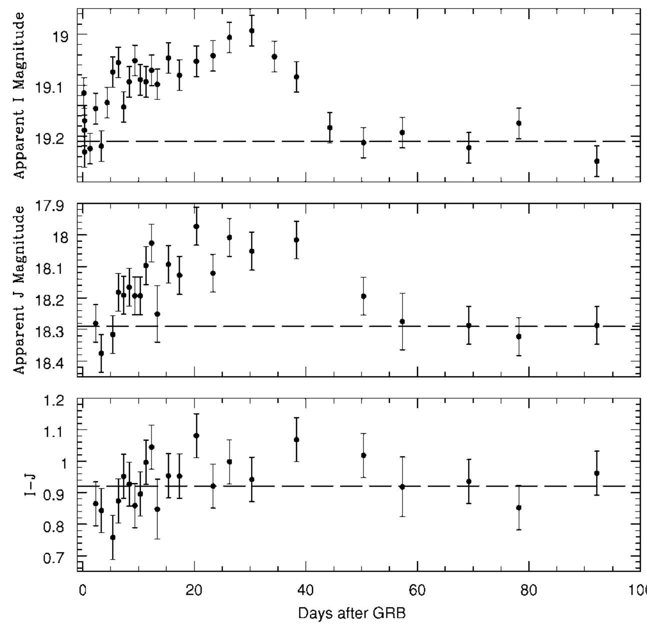

Fig. 1.—*Top panel:* Aperture photometry *I*-band light curve of the host+SN+afterglow of GRB 031203. The dashed line shows the *I* magnitude of the host (19.21). *Middle panel:* Aperture photometry *J*-band light curve of the host+SN+afterglow of GRB 031203. The dashed line shows the *J* magnitude of the host (18.29). The rise and decay in brightness are consistent with a Type Ic SN. These values have not been corrected for Galactic extinction. *Bottom panel:* $I-J$ color evolution; a slight reddening in color may occur as the SN approaches peak brightness. The dashed line shows the $I-J$ color of the host (0.92).

and 18.29 ± 0.03 in *J*. The brightness of the galaxy at peak is determined to be 18.99 ± 0.03 in *I* (the brightness on day 30) and 18.00 ± 0.03 in *J* (the brightness averaged over days 20, 26, and 38). At peak, therefore, the SN increased the total brightness of the galaxy by 0.22 ± 0.03 mag in *I* and 0.29 ± 0.04 mag in *J*. Thus, the combined light may redden slightly as it approaches maximum brightness, although this finding is not particularly robust.

The uncertainty in these measurements is determined from the statistical fluctuation in the measured magnitudes of a nonvariable object with a brightness similar to that of the host galaxy. The relative error is 0.03 mag in *I* and 0.06 mag in *J*. A number of larger errors (0.09 mag) in *J* are due to technical problems that resulted in master *J* frames produced from fewer than 35 individual *J* images. Telescope movement glitches and a malfunction in the IR array also rendered several IR data sets unusable, and hence only 23 data points are determined in *J* while 31 data points are determined in *I*. An additional uncertainty of 0.07 mag in *I* and *J* exists in the transformation of relative to apparent magnitudes.

3.2. *Image-Subtraction Photometry*

Spatially variable kernel-convolved image subtraction was carried out on the *I*-band images using ISIS (Alard 2000). The reference frame that was used for subtraction was formed from the five *I*-band images taken more than 50 days after the GRB, when the SN had faded. The residual light from the SN near peak brightness is clearly evident in the subtracted images. Figure 2 is a "before and after" example of a typical result of this image subtraction.

The centroid of the light from the supernova after subtraction of the galaxy is $0''.041 \pm 0''.049$ west and $0''.054 \pm 0''.062$ south

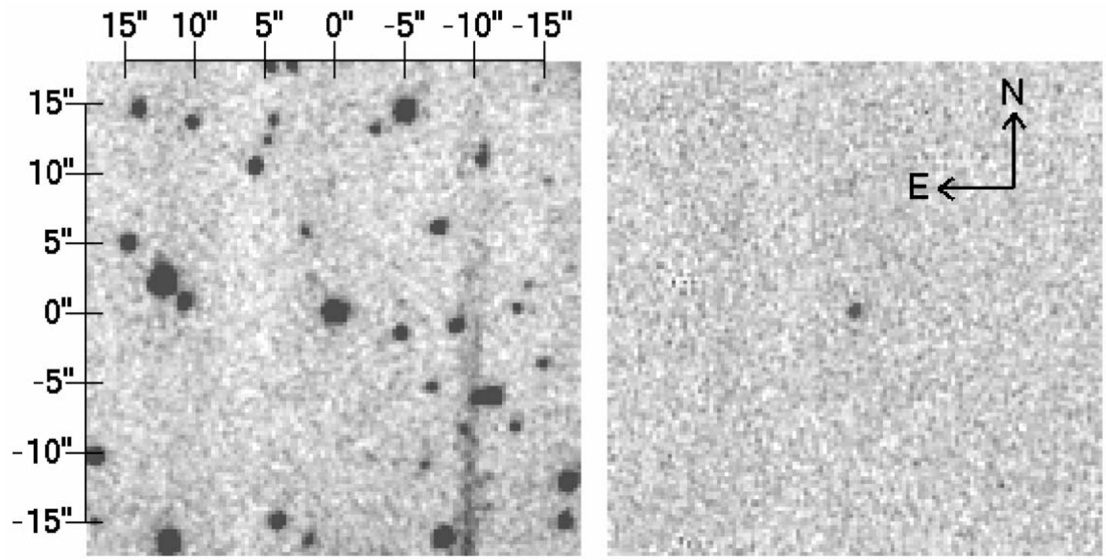

FIG. 2.—Day 26 image before and after kernel-convolved image subtraction with ISIS. The object in the center of the unsubtracted 35″ × 35″ field is the host galaxy of GRB 031203, which is extended in the east-west direction. When a reference frame is subtracted from the image, the residual light from the SN is clearly evident. The reference frame was formed from the five *I*-band images taken more than 50 days after the GRB, when the SN had faded.

of the center of the host galaxy. The position of the SN is, therefore, consistent with the center of the host galaxy. At the distance of the host galaxy, 1″ is 1.91 h_{71}^{-1} kpc in projection, with $H_0 = 71\ h_{71}$ km s^{-1} Mpc^{-1}. Thus, the SN (and by extension the GRB) occurred within 300 h_{71}^{-1} pc (3 σ) of the apparent host center. Only GRB 970508 occurred closer to the host center (Bloom et al. 2002).

4. COMPARISON WITH SN 1998bw

The light curve of the SN associated with GRB 030329 was very similar to that of SN 1998bw. We compared the light curves of SN 2003lw and SN 1998bw to test whether or not they are also similar. SN 1998bw was observed at a lower redshift and without significant background contribution from its host galaxy. The Galactic extinction–corrected light curve of SN 1998bw (Galama et al. 1998) must, therefore, be shifted from $z = 0.0085$ to $z = 0.1055$ and must also be added to the light of the host galaxy of GRB 031203.

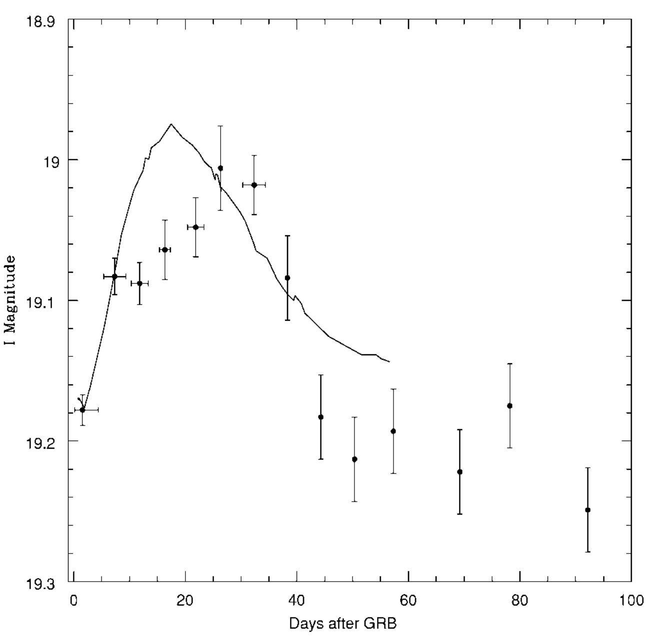

FIG. 3.—Light curve of SN 1998bw moved to $z = 0.1055$ and placed in the host galaxy of GRB 031203 (*solid line*) shown overplotted on the light curve of the host galaxy (*filled circles*), which has been binned using an interval of 5 days. Horizontal error bars reflect the range in time over which the binned data were averaged.

Transforming the light curve of SN 1998bw requires a *k*-correction, stretching, and dimming due both to the change in luminosity distance and to extinction. Wavelengths emitted between the *R* and *I* bands at $z = 0.1055$ are redshifted into the observed *I* band. The light curve of SN 1998bw at a wavelength between the *R* and *I* bands is simply determined by averaging its *R*- and *I*-band magnitudes. This simple *k*-correction is justifiable as the brightness of SN 1998bw was almost identical in these two bands, so it can be assumed that the SN's spectral energy distribution was fairly flat in this wavelength region.

In constructing the SN template, we include a small correction for bandpass stretching of $2.5 \log [(1 + z_{\rm lw})/(1 + z_{\rm bw})] \approx 0.1$ mag, where $z_{\rm lw}$ is the redshift of SN 2003lw and $z_{\rm bw}$ is the redshift of SN 1998bw. Adopting a flat Λ cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1} and $\Omega_m = 0.3$, the luminosity distances for the two SNe are $D_L(z = 0.0085) = 36.6$ Mpc and $D_L(z = 0.1055) = 487.4$ Mpc, a difference in distance modulus of ΔDM = 5.6 mag. SN 1998bw is additionally dimmed by 1.4 mag because of the line-of-sight Galactic extinction toward the host galaxy of GRB 031203. This value is determined from the Galactic reddening of $E(B-V) = 0.78$ toward the host galaxy (Prochaska et al. 2004) and assuming the Galactic extinction curves of Cardelli et al. (1989). This calculation assumes that both SNe have undergone a similar amount of host galaxy extinction, and, therefore, no attempt is made to correct for such extinction. The last step is to add the light of the host galaxy, assuming the host galaxy has an *I* magnitude of 19.21.

Despite the uncertainties inherent in the above procedure, once SN 1998bw is shifted into the host galaxy of GRB 031203, the peak of its light curve is less than 0.1 mag brighter than the inferred peak of SN 2003lw. Figure 3 shows the shifted light curve of SN 1998bw as a solid line overlaid on the light curve of SN 2003lw, which has been binned using an interval of 5 days. Clearly SN 1998bw peaks earlier than SN 2003lw. Note also the dissimilarity of the shapes of these two SNe. There is a poor fit between the SN 2003lw data points and the shifted SN 1998bw curve, with reduced $\chi^2 = 3.68$ calculated from the unbinned data. No combination of stretch and offset of the SN light curve fits the data. This difficulty was not apparent in the data of Thomsen et al. (2004), who had somewhat sparser sampling.

Given the inconsistencies of the template Type Ic and the ANDICAM data, we cannot explicitly conclude from our data alone that the brightening source was due to a Type Ic SN (although Tagliaferri et al. 2004a report spectroscopic evidence of a Type Ic origin). However, local Type Ic SNe show a variety of rise and fall timescales as well as a large range in brightness distributions (e.g., Mazzali et al. 2002), so the differences may simply be inherent in the GRB-related SNe. To be sure, one of the more puzzling emergent trends in GRB-related SNe is why the peak brightnesses of the SNe should be so similar ($M_V \approx -19.5$ mag; see Zeh et al. 2004 and Bloom et al. 2004) while the light curves differ substantially. Since the peak brightness scales roughly as the mass of the synthesized ^{56}Ni (whereas the timescale depends on the mass of the ejecta and the explosion energy; Nomoto et al. 2003), this trend may point to a regularizing mechanism for ^{56}Ni synthesis in SNe associated with GRBs perhaps related to the apparent regularization of energy release in the prompt burst phase (Frail et al. 2001).

We note that there is scant evidence for the existence of the afterglow itself. The peak luminosity of the SN is, therefore, greater than that of the afterglow just a few hours after the GRB. This is in stark contrast to GRB 030329, in which the afterglow after 5 hr was over 5 mag brighter than the peak of the supernova (Lipkin et al. 2004). It is interesting to note that the fluence of the GRB itself (corrected for luminosity distance) was over 2 orders of magnitude smaller in the case of GRB 031203 than GRB 030329 (Ricker 2003; Mereghetti & Gotz 2003). This suggests that there may be a wide range of gamma-ray fluences associated with Type Ic SN events. Recalling that afterglow brightness scales roughly with fluence (Panaitescu et al. 2001), this suggests that *Swift* may reveal a population of faint GRBs whose afterglow light curves are dominated by a supernova, as is the case reported here.

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