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THE *J*-BAND LIGHT CURVE OF SN 2003lw, ASSOCIATED WITH GRB 031203

A. Gal-Yam,[1,2] D.-S. Moon,[1,3] D. B. Fox,[1] A. M. Soderberg,[1] S. R. Kulkarni,[1] E. Berger,[1] S. B. Cenko,[1] S. Yost,[1] D. A. Frail,[4] M. Sako,[5] W. L. Freedman,[6] S. E. Persson,[6] P. Wyatt,[6] D. C. Murphy,[6] M. M. Phillips,[7] N. B. Suntzeff,[8] P. A. Mazzali,[9,10] and K. Nomoto[10]
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ABSTRACT

At $z = 0.1055$, the gamma-ray burst GRB 031203 is the second nearest GRB known. Using observations from the Very Large Array and the *Chandra X-Ray Observatory*, we derive subarcsecond localizations of the radio and X-ray afterglow of this GRB. We present near-infrared observations of the supernova SN 2003lw, which exploded in the host galaxy of GRB 031203. Our deep high-resolution Magellan data establish that this SN is spatially coincident with the radio and X-ray localizations of the afterglow of GRB 031203 to subarcsecond precision and is thus firmly associated with the GRB. We use image differencing to subtract the bright emission from the host galaxy and measure the SN flux at ∼5, ∼7, and ∼50 days after the GRB. Our *J*-band measurements are inconsistent with predictions derived by placing SN 1998bw (associated with GRB 980425) at $z = 0.1055$. In particular, our early data points show that before peak, SN 2003lw was significantly fainter in rest frame ∼1.13 μm (observed *J* band) than SN 1998bw. We measure similar fluxes at ∼7 and ∼50 days after the GRB, suggesting that SN 2003lw had a light-curve shape that is quite different from that of SN 1998bw, the best-studied GRB-associated SN so far.

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

Online material: color figure

1. INTRODUCTION

The emerging association between long-duration gamma-ray bursts (GRBs) and Type Ic supernovae (SNe Ic) is perhaps the most significant breakthrough in our understanding of GRBs. The initial evidence for this connection came from the spatial and temporal coincidence of GRB 980425 and SN 1998bw (Galama et al. 1998). More recently, this picture was convincingly affirmed by the detection of SN features in the optical afterglow spectrum of GRB 030329 (Stanek et al. 2003; Hjorth et al. 2003). These milestone discoveries resulted from the study of the nearest GRBs: GRB 980425 at $z = 0.0085$ and GRB 030329 at $z = 0.1685$. Indeed, each rare occurrence of a GRB at low redshift provides an opportunity for further study of the GRB-SN connection.

GRB 031203 was detected by the *International Gamma-Ray Astrophysics Laboratory* spacecraft on 2003 December 3, at 22:01:28 UT (Gotz et al. 2003). Fading X-ray (Santos-Lleo et al. 2003; Campana et al. 2003; Rodriguez-Pascual et al. 2003) and radio (Frail 2003; Soderberg et al. 2003) afterglows were subsequently discovered. Prochaska et al. (2003a, 2003b, 2004) identified the host galaxy of the X-ray and radio transients, determined its redshift ($z = 0.1055$), and studied its properties. Recently, several groups (Bersier et al. 2004; Thomsen et al. 2004; Cobb et al. 2004; Malesani et al. 2004) reported optical photometric and spectroscopic observations, which reveal the signatures of an associated SN (SN 2003lw; Tagliaferri et al. 2004). In spite of its low redshift, this event is challenging to study because of its low Galactic latitude ($\delta = -4\overset{\circ}{.}8$) and the resulting Galactic extinction [$E(B-V) = 1.04$; Schlegel et al. 1998], as well as its bright host galaxy.

To overcome these difficulties, we have undertaken near-infrared (NIR) observations, presented here. Coordinated radio and X-ray observations, which we used to study the total energy output of this subenergetic GRB, are reported elsewhere (Soderberg et al. 2004).

2. OBSERVATIONS

2.1. *NIR Imaging*

The location of the X-ray and radio transients associated with GRB 031203 was observed with Persson's Auxiliary Nasmyth Infrared Camera (PANIC; equipped with a 1024^2 HgCdTe IR array), mounted on the Baade (Magellan I) 6.5 m telescope, in the J (1.25 μm) and K_s (2.16 μm) bands. The two K_s-band epochs are less deep than the *J*-band data and were obtained ∼5 and ∼72 days after the GRB, when little flux is expected from a SN. Indeed, we did not detect SN 2003lw in K_s and therefore report in this Letter only the analysis of our *J*-band observations. We observed the GRB location at four epochs, 5.38, 7.39, 50.21, and 81.11 days after the burst, and obtained a total of 18, 18, 72, and 36 dithered 120 s exposures in each epoch, respectively. We obtained a common sky frame for each data set from the stacked image cube and subtracted it from each frame. We then carried out flat-fielding and shifted each frame to a common reference position to create the final image.

[1] Division of Physics, Mathematics, and Astronomy, California Institute of Technology, MS 105-24, Pasadena, CA 91125; avishay@astro.caltech.edu.
[2] Hubble Fellow.
[3] Robert A. Millikan Fellow.
[4] National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801.
[5] Chandra Fellow; Kavli Institute for Particle Astrophysics and Cosmology/Stanford Linear Accelerator Center, 2575 Sand Hill Road, M/S 29, Menlo Park, CA 94025.
[6] Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101.
[7] Las Campanas Observatory, Carnegie Observatories, Casilla 601, La Serena, Chile.
[8] Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile.
[9] INAF, Osservatorio Astronomico di Trieste, Via Tiepolo, 11, I-34131 Trieste, Italy.
[10] Department of Astronomy and Research Center for the Early Universe, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan.

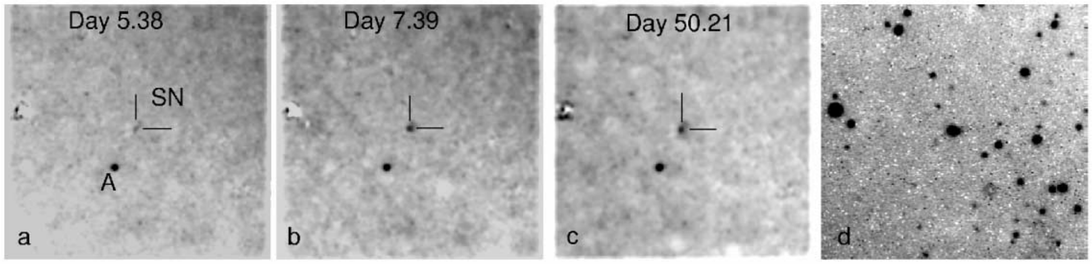

FIG. 1.—NIR detection of SN 2003lw. (*a–c*) $37.''7 \times 37.''7$ sections of the difference images obtained by subtracting our last observed epoch (81.11 days after the GRB) from the first three epochs, obtained at 5.38, 7.39, and 50.21 days postburst. SN 2003lw is at the center of each frame (indicated by crosshairs), and its brightness can be compared to an artificial reference star added to each image ("A" in panel *a*) that has a constant flux. The gray levels in (*a–c*) are linearly scaled between the peak of the artificial reference star and 1 σ of the sky noise below the mode sky level. Comparing (*b*) and (*c*), note the similar IR flux detected at 7 and 50 days after the GRB. For orientation purposes, (*d*) shows a section from our reference PANIC image with the same scale and orientation, centered on the host galaxy of GRB 031203/SN 2003lw. North is up, and east to the left.

2.2. *Image Subtraction and SN Photometry*

In order to extract the faint SN signal from the bright host galaxy background, we have used the Common PSF image-subtraction Method (CPM; A. Gal-Yam et al. 2004, in preparation).[11] We find that extra flux is detected (at greater than 5 σ by SExtractor [ver. 2.3.2; Bertin & Arnouts 1996]) in our three early epochs (5.38, 7.39, and 50.21 days after the GRB) when compared with our latest epoch (day 81.11; see Fig. 1). We therefore proceed with our analysis by assuming that our latest image contains only a negligible amount of SN light. This is supported by *J*-band observations presented by Malesani et al. (2004) and Cobb et al. (2004).

To measure the SN flux in each of the difference frames, we have added an artificial point source, of known negative flux and with the native point-spread function (PSF), to our reference image. This produces a positive artificial star (Figs. 1*a*–1*c*, *bottom left quadrant*) in each of the difference images, which should have an identical PSF to any real variable point source—the native PSF of the reference image convolved with the PSF of the image from which it was subtracted. Using aperture photometry (with the aperture radius equal to the FWHM of the artificial star), we derive the relative photometry of SN 2003lw with respect to this constant source. We use 16 objects appearing in the Two Micron All Sky Survey (2MASS) catalog that are not saturated or nonlinear in our images to tie our zero point to the 2MASS photometry. We then use 10 secondary calibrators in the close vicinity of GRB 031203 to set the absolute calibration of the artificial reference star. From the scatter in photometry derived using different secondary calibrators, we estimate a final absolute calibration error of 0.08 mag. Using this zero point, we calculate the *J*-band magnitudes of SN 2003lw at 5.38, 7.39, and 50.21 days after GRB 031203 to be 21.66 ± 0.60, 20.57 ± 0.21, and 20.60 ± 0.21, respectively (2 σ error bars). Our calibration yields *J*-band magnitudes for the host galaxy and the SN that are consistent with those reported by Cobb et al. (2004).

The main source of error in these magnitudes is the uneven background levels of the difference images, due to nonperfect differencing, flat-fielding, and sky subtraction. In order to quantify this error, we have added 20 artificial point sources to each of the images, at random positions sampling both empty sky and high-background areas, and subtracted the reference image using CPM. We photometered the resulting difference frames and iteratively adjusted the flux of the artificial sources so that their mean flux was equal to that of SN 2003lw at the same epoch. Finally, we adopted the measured scatter in the magnitudes of the artificial sources as the 1 σ error in the SN magnitude at that epoch. We added in quadrature our absolute calibration uncertainty (0.08 mag) and derived the 2 σ (95% confidence level) errors reported above. Poisson errors in the aperture photometry of the bright artificial reference star that we used in our photometric sequence are negligible.

3. RESULTS

3.1. *GRB 031203 and SN 2003lw Are Spatially Coincident*

The position of the radio afterglow from Very Large Array (VLA) observations (Soderberg et al. 2004) is (J2000.0) R.A. $= 08^{h}02^{m}30.^{s}1833(18)$, decl. $= -39^{\circ}51'03.''522(78)$, as referenced to the International Celestial Reference Frame (ICRF; uncertainties in the final digits are given in parentheses). This position is derived from our highest resolution radio observation, the first-epoch 22 GHz map, which had a beam size of $1.''14 \times 0.''29$. It supersedes the radio position that we reported in GCN Circular 2473 (Frail 2003).

The position of the X-ray afterglow is derived from our *Chandra X-Ray Observatory* observations, a single 21.6 ks exposure beginning at 21:35 UT on 2004 January 22 (mean epoch 49.1 days postburst), with the afterglow position at the aim point of the ACIS-S3 CCD. Data were reduced in the standard manner using the CIAO tools (ver. 3.0.2). A *wavdetect* source detection analysis reveals six X-ray sources on the S3 chip with coincident objects in the Guide Star Catalog 2.2 (GSC-2.2). Using these sources we confirm the astrometry relative to the GSC-2.2 to $\pm 0.''13$ precision and derive a position for the afterglow of (J2000.0) R.A. $= 08^{h}02^{m}30.^{s}159$, decl. $= -39^{\circ}51'03.''51$, with $0.''18$ uncertainty, neglecting any systematic uncertainty of the GSC-2.2 frame relative to the ICRF. This position is consistent with the less precise position derived by Tedds et al. (2003). We then identify two X-ray sources on the S3 chip with pointlike sources in our 2003 December 9 PANIC *J*-band image. By registering these two X-ray source positions against their *J*-band counterparts, we are able to locate the afterglow on the PANIC image to $\approx$1.2 pixels ($0.''15$) precision.

[11] CPM compares a new image with a reference one by extracting an empirical PSF from both images and convolving each image with the PSF of the other. While slightly degrading the final seeing (as the final PSF of both images is worse than the initial PSF of either image), this procedure produces output images with nominally identical PSFs, while introducing a minimal amount of noise. In particular, we have found that this algorithm often produces difference images that have lower subtraction residuals near the nuclei of bright galaxies compared to other image subtraction packages, and thus allows better sensitivity to variable sources that are superposed on a bright galactic background.

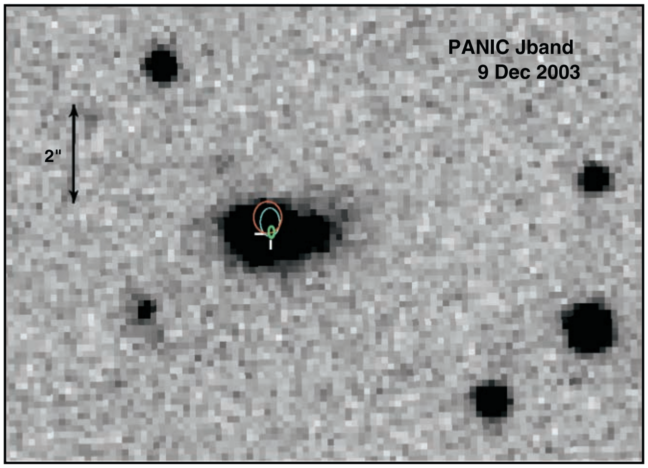

FIG. 2.—PANIC *J*-band image of the host galaxy of GRB 031203 from 2003 December 9, with localizations of the *Chandra* X-ray afterglow (*red*), the VLA radio afterglow (*cyan*), and the PANIC NIR transient (*green*) superposed; the position of the central maximum of the host galaxy light is indicated by the white ticks. North is up, and east is to the left. The ellipses shown are 2 σ (95% confidence) localizations; see text for details. The NIR transient ellipse is 0.46 × 0.92 pixels (0″.06 × 0″.11) in size. The size of the VLA ellipse is 0″.38 × 0″.58; the X-ray ellipse is 0″.56 × 0″.64. Although transient light contributes to this image, its effect on the appearance of the host galaxy at this color stretch is negligible. The localizations of the afterglow and transient are consistent across all wavelengths and locate the source within 0.2 kpc of the central maximum of the host galaxy light.

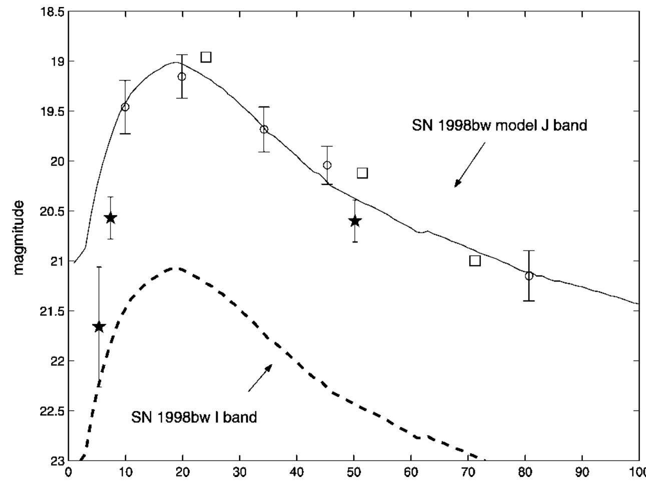

FIG. 3.—*J*-band photometry of SN 2003lw. Our measurements (stars with 2 σ error bars; see text) are compared to a model light curve of SN 1998bw. The dashed line shows the *I*-band light curve of SN 1998bw, redshifted to $z = 0.1055$ and corrected for Galactic extinction ($A_I = 1.4$ mag; Cobb et al. 2004) and an additional extinction at the host estimated by Prochaska et al. (2004) to be $A_V \sim 1$ mag ($A_I = 0.6$ mag). NIR spectra of SN 1998bw (Patat et al. 2001), as well as synthetic spectra from Iwamoto et al. (1998), are used to calculate $I - J$ color offsets and predict the *J*-band flux at the epochs of the spectra, correcting for the appropriate *J*-band extinction (see text). Predictions based on the Patat et al. (2001) spectra are plotted as squares and those based on the synthetic Iwamoto et al. (1998) spectra as circles. Combined, they serve as our guidance in constructing a model *J*-band light curve for SN 1998bw, by adopting the *I*-band light curve shape, normalized to fit these points (*solid curve*). Note that the model is inconsistent with our early data points. [*See the electronic edition of the Journal for a color version of this figure.*]

The resulting 2 σ (95% confidence level) X-ray localization, 0″.56 × 0″.64 in size, is shown as the red ellipse in Figure 2, along with the 2 σ VLA radio (*cyan*) and PANIC NIR transient (*green*) localizations, as transferred to the same image. The world coordinate system on the PANIC image is derived from the positions of 23 2MASS counterparts, and the uncertainty in the VLA position is dominated by the 0″.095 × 0″.121 rms of this mapping. NIR localizations are derived from two of our subtracted images, which differ by (0.23, 0.46) pixels, so we adopt 0″.029 × 0″.058 as our 1 σ uncertainty. Figure 2 shows that the location of the NIR transient is consistent with that of the afterglow across all wavelengths, to high precision, confirming the association that has already been inferred from the temporal coincidence of GRB 031203 and SN 2003lw. Moreover, this location is consistent with the peak of the host galaxy light: the NIR offset, which has the highest precision, is 0.15 ± 0.23 pixels west, 0.26 ± 0.46 pixels north. At $z =$ 0.1055, this 0″.04 ± 0″.06 offset corresponds to a physical distance of 0.07 ± 0.13 kpc.

3.2. *The J-Band Light Curve*

Figure 3 shows the *J*-band light curve of SN 2003lw. Our deep observations detect the SN light ∼5 days after the burst and suggest a steep rise in flux between ∼5 and ∼7 days after the GRB. The flux measurements at ∼7 and ∼50 days after the GRB are comparable.

To better interpret these observations, we wish to compare our data to the *J*-band light curve of SN 1998bw, the prototype and best-observed GRB-associated SN. Unfortunately, the only data available are three epochs of NIR photometry and spectroscopy (Patat et al. 2001). Thus, our strategy is to model the *J*-band light curve of SN 1998bw, as it would seem at $z =$ 0.1055, by shifting the appropriate *I*-band light curve by a constant $I - J$ color offset. We check the validity of this approach below. On the basis of the observations of Galama et al. (1998), we construct the *I*-band light curve of SN 1998bw at $z = 0.1055$ (Fig. 3, *dashed curve*). We use optical and IR spectra from Patat et al. (2001) to calculate the $I - J$ colors of SN 1998bw, redshifted to $z = 0.1055$, using the methods described by Poznanski et al. (2002). We find $I - J =$ (1.14, 1.17, 1.12) at (22.4, 47.4, 65.4) days after GRB 980425 (corresponding to 24.8, 52.4, and 79.3 days at $z = 0.1055$). Iwamoto et al. (1998) present models of exploding C+O stars that reproduce the optical light curve and spectra of SN 1998bw. We use these model synthetic spectra, extending to 1.2 μm, to calculate $I - J$ colors of SN 1998bw as we have done with the real data. Errors resulting from incomplete coverage of the *J*-band by the spectra are calculated as in Poznanski et al. (2002). We find $I - J =$ (1.07 ± 0.27, 0.88 ± 0.22, 0.81 ± 0.23, 0.98 ± 0.19, 0.80 ± 0.25, 1.13 ± 0.28) at (9, 18, 31, 41, 73, 98) days after GRB 980425 (9.9–108.3 days at $z = 0.1055$). We adjust the *I*-band light curve by the mean of the color measurements that we have, $I - J = 1.01$, and further correct it for Galactic extinction of $A_J = 0.67$ and an additional extinction at the SN host of $A_V \sim 1$ mag ($A_J = 0.28$ mag; Prochaska et al. 2004), yielding the solid curve plotted in Figure 3. We assume that the extinction toward SN 1998bw was negligible ($A_V < 0.15$; Patat et al. 2001). Note that the solid curve provides a reasonable fit to all the individual *J*-band anchor points available, and thus the use of the average color (equivalent to assuming that the *I*- and *J*-band light curves have similar shapes) is justified. Interestingly, the rough $I - J$ colors of SN 2003lw measured by Cobb et al. (2004; Fig 1; $I - J \sim 1$) appear similar to the colors that we derive for SN 1998bw at $z = 0.1055$.

Comparing the model SN 1998bw light curve with our observations, a discrepancy is revealed. While our late-time point is consistent with the model, the early-time data points fall significantly below model expectations, with our well-measured day 7.39 point fainter by ∼0.6 mag, a 6 σ effect. This discrepancy is enhanced if SN 2003lw is intrinsically brighter than SN 1998bw by ∼0.4 mag, as advocated by Thomsen et al. (2004) and Malesani et al. (2004). We also note that the fast early rise implied by our early data points is not reproduced by the model. We argue that SN 2003lw had a different *J*-band light curve *shape*, rather than being a fainter (or more dust obscured; additional extinction of $A_V \sim 1.5$ mag needs to be invoked) twin of SN 1998bw, since the latter alternatives would conflict with both our NIR data and optical observations by Thomsen et al. (2004), Cobb et al. (2004), and Malesani et al. (2004).

4. DISCUSSION AND CONCLUSIONS

In this Letter, we have presented *J*-band observations of SN 2003lw. We pinpoint the location of SN 2003lw within its host galaxy and show that it is consistent with subarcsecond localizations of the radio and X-ray afterglow of GRB 031203, thus confirming the association of these two events. The precise NIR localization of this event also puts it within 0.2 kpc from the host galaxy center. The *J*-band light curve of SN 2003lw shows a rapid initial rise (5–7 days after the GRB) and evidence for bright emission more than 50 days after the GRB. The fast early rise of SN 2003dh, associated with GRB 030329, has been interpreted by Woosley & Heger (2003) and Mazzali et al. (2003) as evidence for asymmetry in the explosion. A thorough investigation of this possibility will probably require an analysis of our data in combination with extensive data sets collected by other groups (e.g., Thomsen et al. 2004; Malesani et al. 2004; Bersier et al. 2004; Cobb et al. 2004).

Cobb et al. (2004) reported *I*- and *J*-band observations of this event. A direct comparison between our observations and their data is complicated by the fact that these authors do not present the light curve of SN 2003lw. Instead, they plot the temporal evolution of the combined light of the SN and its bright host galaxy, derived from aperture photometry, which shows considerable scatter. It is thus hard to say whether their data show the same early fast rise that we detect. Our finding that SN 2003lw had similar flux levels 7 and 50 days after the GRB is consistent with the Cobb et al. data. Malesani et al. (2004) and Cobb et al. (2004) find that the optical light curves of SN 2003lw were different from those of SN 1998bw. Combined with our findings, it appears that SN 2003lw had a light curve quite unlike that of SN 1998bw—with a fast rise to maximum, which appears broader, and perhaps showing a secondary peak in the IR.

The above discussion provides further evidence for the diversity of SNe associated with GRBs (see, e.g., Thomsen et al. 2004 and Lipkin et al. 2003 for recent reviews). It may well be the case that the focus of future studies should now move from proving the association between SNe and GRBs to an attempt to characterize the properties of this population of SNe. Such studies may provide new clues about the progenitors and engines of GRBs by requiring viable GRB models to be able to produce the large quantities of nickel derived from the SN observations, as well as valuable insights into possible explosion mechanisms of core-collapse SNe, which may involve GRB-like aspherical effects (e.g., Khokhlov et al. 1999; see Gal-Yam et al. 2004 for further discussion). Low-redshift GRBs, expected to be localized in larger numbers by the upcoming *Swift* mission, as well as systematic studies of local core-collapse SNe (e.g., Berger et al. 2003; A. M. Soderberg et al. 2004, in preparation; Stockdale et al. 2004), will probably shed more light on these intriguing questions.

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