The Astrophysical Journal, 645: L21–L24, 2006 July 1

EARLY-TIME PHOTOMETRY AND SPECTROSCOPY OF THE FAST EVOLVING SN 2006aj ASSOCIATED WITH GRB 060218[1]

M. Modjaz,[2] K. Z. Stanek,[3] P. M. Garnavich,[4] P. Berlind,[5] S. Blondin,[2] W. Brown,[2] M. Calkins,[5] P. Challis,[2] A. M. Diamond-Stanic,[6] H. Hao,[2] M. Hicken,[2] R P. Kirshner,[2] and J. L. Prieto[3]
Received 2006 March 15; accepted 2006 May 17; published 2006 June 21

ABSTRACT

We present early photometric and spectroscopic data on the afterglow of GRB 060218 and report the evolution of the underlying supernova SN 2006aj. Our data span a time range of 4–23 days after the GRB and clearly establish that SN 2006aj is a fast-evolving broad-lined Type Ic SN with an extremely short rise time (∼10 days) and a large optical peak luminosity ($M_V = -18.7$ mag). The supernova properties are deduced well since the gamma-ray burst (GRB) afterglow does not contribute a significant amount to the total light output. The spectra show broad lines indicative of large expansion velocities but are better matched by those of SN 2002ap and SN 1997ef (not associated with a GRB) than those of the prototypical GRB-related SN 1998bw. We refine the redshift estimate to $z = 0.03351 \pm 0.00007$. The host galaxy is a low-metallicity dwarf galaxy (with $M_{V,\,\mathrm{host}} = -16.0$ mag), similar to host galaxies of other GRB-associated SNe.

Subject headings: galaxies: distances and redshifts — gamma rays: bursts — supernovae: general — supernovae: individual (SN 2006aj)

Online material: color figure

1. INTRODUCTION

The connection between long-duration gamma-ray bursts (GRBs) and supernovae (SNe) that arise from the core collapse of very massive stars stands on firm footing (see, e.g., Stanek 2005 for a recent review). Circumstantial evidence includes the location of GRBs near sites of massive star formation (Bloom et al. 2002) and the detection of unusual "bumps" in the GRB afterglow light curves that mimic a SN light curve and its colors (e.g., Bloom et al. 1999; Garnavich et al. 2003). More importantly, there are two cases of direct associations: the temporal and spatial coincidence between SN 1998bw and GRB 980425 (Galama et al. 1998) and the metamorphosis of the GRB 030329 spectrum into that of a supernova, called SN 2003dh (Stanek et al. 2003; Hjorth et al. 2003; Matheson et al. 2003; Kawabata et al. 2003; Kosugi et al. 2004). Based on spectra, SN 1998bw and SN 2003dh were classified as peculiar Type Ic SNe (SNe Ic), that is, core-collapse SNe that showed no hydrogen nor helium in their spectra, but unusually high expansion velocities requiring high explosion energies (Galama et al. 1998; Iwamoto et al. 1998; Patat et al. 2001; Mazzali et al. 2003), in line with the collapsar model for long-duration GRBs (Woosley 1993; MacFadyen & Woosley 1999). There is some evidence of spectroscopically confirmed supernovae for other GRBs, however, with less confidence (Della Valle et al. 2003; Malesani et al. 2004). Spectral confirmation of GRB-related SNe is crucial since spectra provide understanding of the velocity and nucleosynthesis structure of the ejecta and give an insight into the energetics of the SN explosion. Here we report on the spectral and photometric evolution of GRB 060218/SN 2006aj.

On 2006 February 18, at 03:34:30 UT, the Burst Alert Telescope (BAT) on board the *Swift* Gamma-Ray Burst Explorer detected the bright GRB 060218 (Cusumano et al. 2006). *Swift* X-Ray Telecope (XRT) and UV/Optical Telescope (UVOT) also detected its afterglow in the X-ray (Cusumano et al. 2006; Kennea et al. 2006) and optical bands (Cusumano et al. 2006) that lead to a precise determination of the optical counterpart's position as R.A. $= 03^{\mathrm{h}}21^{\mathrm{m}}39\overset{\mathrm{s}}{.}71$ and decl. $= +16^{\circ}52'02\overset{\prime\prime}{.}6$ (equinox J2000.0; Marshall et al. 2006b). GRB 060218 lasted about 2000 s (Barthelmy et al. 2006), establishing it as one of the longest GRBs, and had peculiar gamma-ray and X-ray afterglow properties (Gehrels et al. 2006). Due to the unusual properties and relative brightness of GRB 060218, extensive and rapid follow-up observations in all wavelength bands ensued around the globe. Spectroscopic observations of the host galaxy, which had been detected in preburst images by the Sloan Digital Sky Survey (SDSS; Cool et al. 2006), and of the optical transient (OT) were undertaken by several groups. Their spectra revealed a blue continuum due to the afterglow light, narrow host galaxy emission lines at a redshift of $z = 0.033$ (Mirabal & Halpern 2006a), and broad spectral features characteristic of a supernova (Masetti et al. 2006; Soderberg et al. 2006b; Mazzali & Pian 2006; Fugazza et al. 2006; Fathkhullin et al. 2006), which was designated SN 2006aj (Soderberg et al. 2006a; Mirabal & Halpern 2006b; Fugazza et al. 2006). SN 2006aj was visible at $\Delta T \sim 2$ days (where ΔT is time after burst) in the rest frame of the GRB (Masetti et al. 2006; Mirabal & Halpern 2006b), much earlier than GRB 030329/SN 2003dh (where the SN was visible at $\Delta T \sim 8$ days in the rest frame). With a redshift of $z = 0.033$, this is the lowest redshift GRB/SN after GRB 980425/SN 1998bw ($z = 0.0085$), and closer than GRB 030329/SN 2003dh at $z = 0.1685$.

Due to its proximity and early emergence of the SN, a densely time-sampled and high-quality study of GRB 060218/SN 2006aj can shed light on GRB-related core-collapse SNe, their explosion

[1] Observations reported here were obtained at the MMT Observatory, a joint facility of the Smithsonian Institution and the University of Arizona.

[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; mmodjaz@cfa.harvard.edu, sblondin@cfa.harvard.edu, wbrown@cfa.harvard.edu, pchallis@cfa.harvard.edu, hhao@cfa.harvard.edu, mhicken@cfa.harvard.edu, kirshner@cfa.harvard.edu.

[3] Department of Astronomy, Ohio State University, Columbus, OH 43210; kstanek@astronomy.ohio-state.edu, prieto@astronomy.ohio-state.edu.

[4] Department of Physics, 225 Nieuwland Science Hall, University of Notre Dame, Notre Dame, IN 46556; pgarnavi@nd.edu.

[5] Smithsonian Institution, Fred Lawrence Whipple Observatory, 670 Mount Hopkins Road, P.O. Box 97, Amado, AZ 85645.

[6] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721.

mechanism, and progenitor history. Here we present such a data set of spectroscopic and photometric observations.

2. OBSERVATIONS

After the announcement of the SN-GRB association via the GRB Coordinates Network (GCN), we promptly established our monitoring program of GRB 060218/SN 2006aj. Spectra and photometry were obtained on a nearly nightly basis starting UT 2006 February 22 with the 6.5 m Multiple Mirror Telescope (MMT) and the 1.5 m Tillinghast and 1.2 m telescopes at the Fred Lawrence Whipple Observatory (FLWO). The spectrographs utilized were the Blue Channel (Schmidt et al. 1989) at the MMT, and FAST (Fabricant et al. 1998) at the FLWO 1.5 m telescope. All optical spectra were reduced and calibrated employing standard techniques in IRAF[7] and our own IDL routines for flux calibration.

All of our photometry data were obtained with the FLWO 1.2 m telescope. In this Letter we report on 26 *V*-band points obtained between 2006 February 22 and March 13 UT, i.e., between 4 and 23 days after the burst. The light curve was extracted using the ISIS2 image subtraction package (Alard 2000). To obtain absolute calibration, we observed Landolt standards (Landolt 1992) on 2006 March 4 UT. The derived transformation coefficients and color terms were used to calibrate a sequence of nine stars near SN 2006aj. For future references and cross-calibrations, this transformation gives $V = 15.21 \pm 0.01$ mag for the SDSS star at R.A. = $03^{\mathrm{h}}21^{\mathrm{m}}42^{\mathrm{s}}.77$ and decl. = $+16°51'39''.46$ (J2000.0). The absolute photometric calibration is thought to be accurate to ~5%. We note that our calibration yields comparison star magnitudes in the SDSS *griz* system[8] that are fainter than those given in Cool et al. (2006). The offsets in the respective bands are +0.81 mag (u'), +0.40 mag (B), +0.27 mag (V), +0.20 mag (R), +0.23 mag (r'), and +0.15 mag (i'). Using the same transformation, we obtain $V = 20.21$ mag for the host galaxy, using data from Cool et al. (2006) and our own Landolt calibrations.

3. RESULTS

3.1. *GRB 060218/SN 2006aj*

Figure 1 shows a montage of our spectra, corrected for a Galactic extinction of $A_V = 0.46$ mag (Schlegel et al. 1998). We do not correct for host-galaxy extinction, which is constrained to be small, namely, $E(B-V) \sim 0.04$ mag from the equivalent widths of Na I D lines in high-resolution spectra (Guenther et al. 2006). On top of a smooth power-law continuum that is typical of GRB afterglows are undulations characteristic of a "broad-lined" SN Ic: broad blends of Fe II and Si II λ6355, while no hydrogen or helium absorption lines are detected. The SN signatures are visible in our earliest spectrum at observed $\Delta T = 3.97$ days and become stronger as a function of time. The narrow lines are common nebular lines and identified as Hα, [O III] λ5007, Hβ, and [O II] λ3727 at $z = 0.03351 \pm 0.00007$ arising from H II regions in the host galaxy. Assuming $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 72$ km s^{-1} Mpc^{-1}, this corresponds to a luminosity distance of 143 Mpc. Using the value for the fluence detected by *Swift* (Campana et al. 2006), GRB 060218 appears to be an underluminous event in

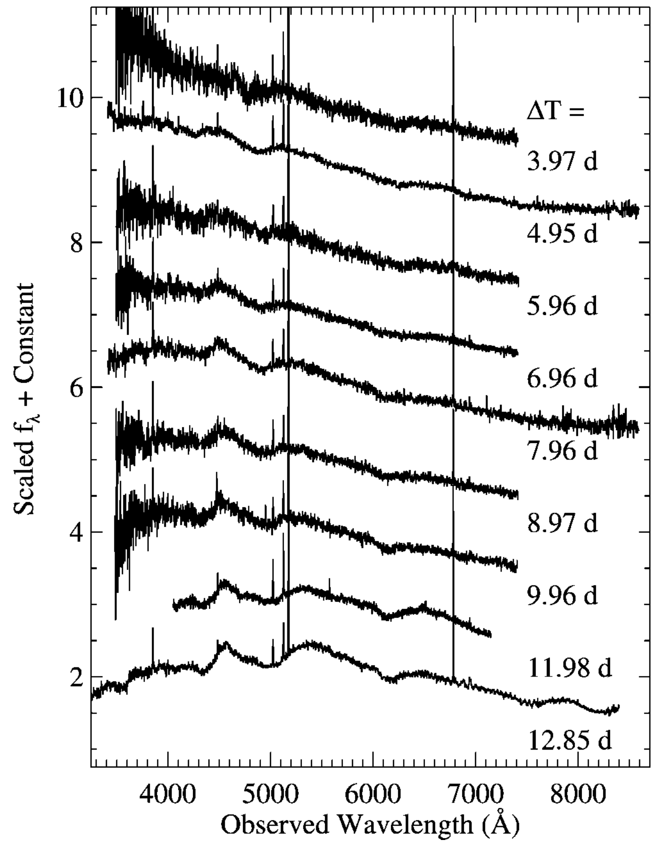

FIG. 1.—Observed spectral evolution of the GRB 060218/SN 2006aj, from February 22.12 UT (3.97 days after the burst) to March 3.00 UT (12.85 days after the burst), dereddened by $A_V = 0.46$ mag of Galactic extinction (Schlegel et al. 1998). The spectra consist of a power-law continuum, typical of GRB afterglows, and the broad features characteristic of a peculiar, broad-lined SN Ic. The narrow emission lines originate from the host galaxy at a redshift of $z = 0.0335$.

gamma rays: the isotropic equivalent energy amounts to $E_{\mathrm{iso}} = 6 \times 10^{49}$ ergs (extrapolated to 1–10,000 keV band in the GRB rest frame), which is $\sim 10^{-2}$ to 10^{-1} that of cosmological GRBs (e.g., Ghirlanda et al. 2005; Friedman & Bloom 2005) but larger than that for GRB 980425/SN 1998bw. The gamma-ray peak luminosity is $L_{\mathrm{peak}} = 5 \times 10^{46}$ ergs s^{-1} (see also Sakamoto et al. 2006; Campana et al. 2006).

Figure 2 presents our early *V*-band light curve for GRB 060218/SN 2006aj (*filled circles*). In addition to our FLWO 1.2 m data, we have added some data from the literature to extend our time coverage, namely, four early *V*-band points from *Swift* UVOT as reported by Marshall et al. (2006a, 2006b) and Nousek et al. (2006). Campana et al. (2006) present *Swift* early-time data ($\Delta T < 10^6$ s, or 11.6 days) of GRB 060218/SN 2006aj and argue for tantalizing evidence of an observed thermal shock-breakout along with the GRB afterglow thousands of seconds after the collapse of the core. Our *V*-band data clearly show a second peak and the shape of a "supernova bump." The combined GRB afterglow/shock breakout decline very quickly, and the SN component dominates the OT light early on ($\Delta T \geq 3$ days) and certainly when our spectra were obtained. At those times, SN 2006aj is 6–13 times brighter than the host galaxy. To compare the behavior of this bump, we used the *V*-band light curve of SN 1998bw (Galama et al. 1998), shifted to $z = 0.0335$ and dimmed by $A_V = 0.46$ mag due to the Galactic extinction (Schlegel et al. 1998; Fig. 2, *dotted line*). We find that the SN 2006aj associated with GRB 060218 evolved much faster than SN 1998bw. Indeed,

[7] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[8] Using the transformation equations of R. Lupton; see http://www.sdss.org/dr4/algorithms/sdssUBVRITransform.htm.

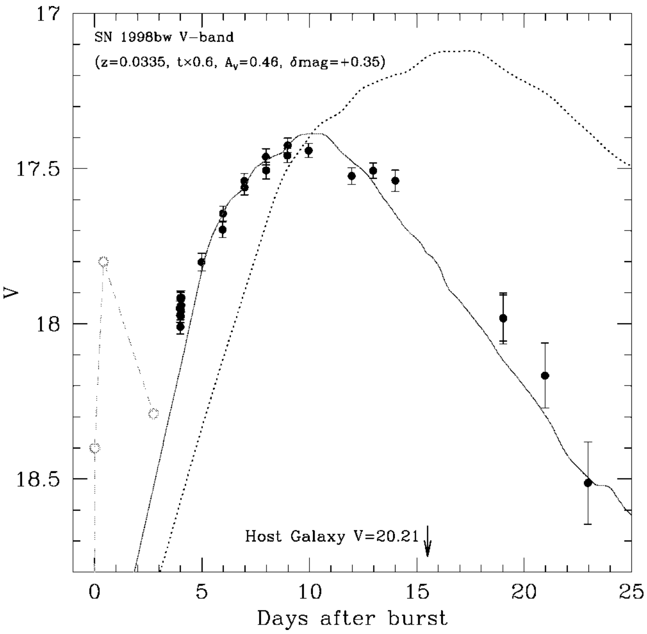

FIG. 2.—Observed V light curve of GRB 060218/SN 2006aj based on the FLWO 1.2 m data (*filled points*) and *Swift* UVOT data taken from the GCN (*open points*). Superimposed is the V light curve of SN 1998bw, k-corrected and time-dilated to $z = 0.0335$, stretched by a factor of 0.6, dimmed by 0.46 mag of Galactic extinction, the SN host galaxy contribution added, and shifted by 0.35 mag to match that of SN 2006aj (*solid line*). No correction for host galaxy extinction has been applied to SN 2006aj or the comparison light curve of SN 1998bw. See § 3 for details. [*See the electronic edition of the Journal for a color version of this figure.*]

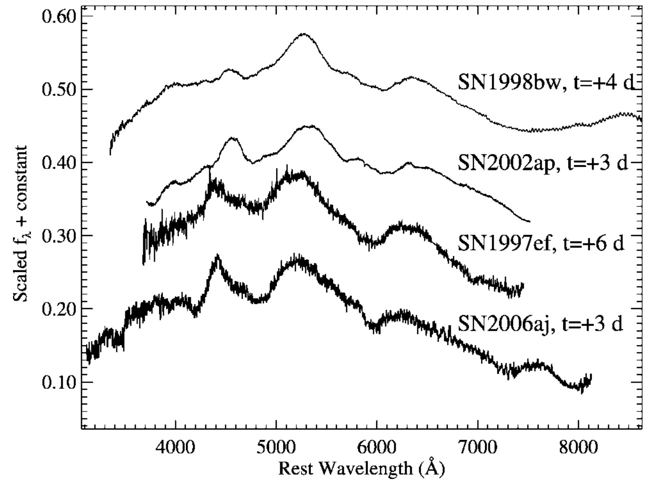

FIG. 3.—MMT spectrum of GRB 060218/SN 2006aj taken on March 03.00 UT, which corresponds to $\Delta T = 12.85$ days after the burst and ~3 days after V maximum. The broad absorption trough at 5900 Å due to blueshifted Si II λ6355 is visible, as well as the broad Fe II blends at ~4400 Å and O I λ7774 at 7300 Å. For clarity, the host galaxy emission lines have been removed and the spectra have been scaled and shifted. From the sample of representative spectra of broad-lined SNe Ic at comparable phases, it is clear that SN 1997ef and SN 2002ap are better matches than SN 1998bw.

we find a good fit to our V-band data if we stretch the time axis of the light curve of SN 1998bw by a "stretch factor" of $s = 0.6$. The combined fit of the $V = 20.21$ mag host galaxy (Cool et al. 2006) added to the stretched SN 1998bw V-band light curve dimmed by 0.35 mag is shown with the solid line. Our V-band light curve of SN 2006aj peaks at $\Delta T = 10.0 \pm 0.5$ days (i.e., 2006 February 28.15 UT and at $\Delta T = 9.7$ days in the rest frame of SN 2006aj) at an apparent magnitude $m_V = 17.45 \pm 0.05$ mag. After correcting for a Galactic extinction of $A_V = 0.46$ mag and host galaxy light contamination, this value corresponds to a peak absolute magnitude of $M_V = -18.7 \pm 0.2$ mag for SN 2006aj. The rise time for SN 2006aj is the shortest ever measured for a SN Ic and is significantly shorter than for GRB 980425/SN 1998bw and GRB 030329/SN 2003dh (~14–16 days; Galama et al. 1998; Matheson et al. 2003), while SN 2006aj is almost as bright as SN 1998bw. This is an unusual behavior compared to the sample of GRB-related SNe (see Fig. 3 in Stanek et al. 2005). We note that there is a hint of a short plateau phase between ~12 and 15 days after the burst. *Thus, we conclude that SN 2006aj is a fast-evolving SN and that the SN dominated the light of the OT.*

In order to study the SN component of GRB 060218/SN 2006aj more closely, we plot in Figure 3 our MMT spectrum from UT 2006 March 03, at $\Delta T = 12.85$ days, thus ~3 days after V maximum, when the SN fully dominates the total light output. The broad absorption trough at 5900 Å (rest wavelength) due to blueshifted Si II λ6355 is visible, as well as the broad Fe II blends at ~4400 Å, while no lines of hydrogen or helium are detected. For comparison, we show spectra of other broad-lined SNe Ic at similar phases: the classical SN 1998bw (Patat et al. 2001), the SNe 1997ef (Iwamoto et al. 2000), and 2002ap (Foley et al. 2003; M. Modjaz et al. 2006, in preparation). The spectrum of SN 2006aj exhibits features that are more well defined and narrow than those of SN 1998bw, which indicates that the expansion velocities in SN 2006aj were lower than in SN 1998bw and, by extension, in SN 2003dh. Our earlier spectra of SN 2006aj in addition to this spectrum are very similar to those of SN 1997ef and SN 2002ap, which are broad-lined SNe that had no obvious association with GRBs and are thought to be due to less energetic explosions than SN 1998bw (Iwamoto et al. 2000; Foley et al. 2003). This visual match is supported by cross-correlating the spectra with our comprehensive library of SN Ic and GRB/SN spectra (M. Modjaz et al. 2006, in preparation) via our SN-identification algorithm (Matheson et al. 2005; S. Blondin et al. 2006, in preparation). Thus, the spectra of SNe associated with GRBs seem to display a certain variety of expansion velocities. Considering both the light curve and spectral properties of SN 2006aj, we conclude that its expansion velocities lie between that of SN 1998bw and of SN 2002ap, while a large synthesized ^{56}Ni mass is needed to explain the large luminosity, in addition to a geometry and ejecta mass that support the fast escape of photons. We encourage polarization studies and nebular line spectroscopy to constrain the geometry of the explosion. Also, late-time observations should give a cleaner window into the core of the ejecta and help constrain density distribution and the abundance of nucleosynthesis products.

3.2. *Host Galaxy*

For the adopted luminosity distance of 143 Mpc, the preburst broadband SDSS photometry yields an absolute magnitude for the host galaxy of $M_{V,\mathrm{host}} = -16.0$ mag. This value is less than that for the Small Magellanic Cloud, a dwarf galaxy with $M_V = -16.9$ mag. We generated a spectrum of the host galaxy emission lines by averaging the MMT spectra and subtracting a lower order fit to the continuum. The emission-line fluxes were measured with the `splot` task in IRAF and are given here corrected for Galactic extinction and normalized to Hβ [where $F(\mathrm{H}\beta) = 0.9 \pm 0.1 \times 10^{-15}$ ergs cm^{-2} s^{-1}]: Hβ = 1.0, Hα = 3.0, Hγ = 0.3, [O III] λ4959 = 1.2, [O III] λ5007 = 4.0, [O II] λ3727 = 1.6, and [N II]

$\lambda6584 < 0.2$ (not detected, 1 σ upper limit). Comparison of the line fluxes with the broadband SDSS photometry (Cool et al. 2006) indicates that the host galaxy contribution to the continuum flux is negligible and becomes important only at very short wavelengths (3000–4000 Å). The relative strengths of the Balmer lines indicate little host galaxy extinction with $E(B-V) \sim 0.05$–0.11 mag. We derive an integrated Hα luminosity of $L(\mathrm{H}\alpha) = 7.3 \times 10^{39}$ ergs s^{-1}, which translates to a current star formation rate of SFR(Hα) $= 0.06\ M_\odot$ yr^{-1} (Kennicutt 1998). This lower limit is relatively high for such an underluminous galaxy. In order to derive the metallicity of the host system, we used the R_{23} iterative diagnostic that involves the emission-line ratios of [O II] $\lambda3727$, [O III] $\lambda5007$, [N II] $\lambda6584$, and Hβ (Kewley & Dopita 2002). We derive an ionization parameter of $q \sim 8 \times 10^7$ cm s^{-1} and an oxygen abundance of $\log(\mathrm{O/H}) + 12 = 8.0 \pm 0.1$, which corresponds to about 0.15 $Z_\odot$, assuming a solar abundance of $\log(\mathrm{O/H}) + 12 = 8.86$ (Delahaye & Pinsonneault 2006). We note that the R_{23} diagnostic also possesses an upper branch that predicts an oxygen abundance of $\log(\mathrm{O/H}) + 12 = 8.7 \pm 0.1$. However, this upper branch is excluded by considering the upper limit on [N II] $\lambda6584$ (see Kewley & Dopita 2002, Fig. 7). Furthermore, the higher oxygen abundance would predict a much brighter host galaxy according to the luminosity-metallicity relationship (e.g., Lee et al. 2003; Tremonti et al. 2004). Thus, we conclude that the host galaxy of GRB 060218/SN 2006aj is a low-metallicity, low-luminosity galaxy, very similar to those of other GRBs/SNe (e.g., Matheson et al. 2003; Sollerman et al. 2005) and those of more distant GRBs (e.g., Fruchter et al. 1999; Le Floc'h et al. 2003).

4. CONCLUSIONS

We have presented early photometric and spectroscopic data on GRB 060218/SN 2006aj that clearly establish SN 2006aj as a fast-evolving broad-lined SN Ic with an extremely short rise time and a large optical peak luminosity at $z = 0.0335$. The spectra indicate large expansion velocities that are smaller than those found in the prototypical GRB-related SN 1998bw. The host galaxy appears to be a low-metallicity dwarf galaxy.

We would like to thank the staffs of the MMT Observatory and FLWO. In particular we would like to acknowledge C. Tremonti and G. Williams for obtaining some of the spectra, and the observers at the FLWO 1.2 m for obtaining service photometry. M. M. thanks T. Matheson for useful comments on the manuscript and M. Geller, L. Kewley, and A. Friedman for helpful discussions. We thank the *Swift* team and the observers who provided their data and analysis through the GCN. Supernova research at Harvard University has been supported by a grant from the National Science Foundation, AST 02-05808.

Facilities: MMT(Blue Channel spectrograph), FLWO: 1.5m(FAST), FLWO:1.2m(Keplercam)

REFERENCES

Alard, C. 2000, A&AS, 144, 363
Barthelmy, L., Cummings, J., Sakamoto, T., Markwardt, C., & Gehrels, N. 2006, GCN Circ. 4806, http://gcn.gsfc.nasa.gov/gcn/gcn3/4806.gcn3
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Bloom, J. S., et al. 1999, Nature, 401, 453
Campana, S., et al. 2006, Nature, in press (astro-ph/0603279)
Cool, R. J., et al. 2006, GCN Circ. 4777, http://gcn.gsfc.nasa.gov/gcn/gcn3/4777.gcn3
Cusumano, G., Barthelmy, S., Gehrels, N., Hunsberger, S., Immler, S., Marshall, F., Palmer, D., & Sakamoto, T. 2006, GCN Circ. 4775, http://gcn.gsfc.nasa.gov/gcn/gcn3/4775.gcn3
Delahaye, F., & Pinsonneault, M. 2006, ApJ, in press (astro-ph/0511779)
Della Valle, M., et al. 2003, A&A, 406, L33
Fabricant, D., Cheimets, P., Caldwell, N., & Geary, J. 1998, PASP, 110, 79
Fathkhullin, T. A., Sokolov, V. V., Moiseev, A. V., Guziy, S., & Castro-Tirado, A. J. 2006, GCN Circ. 4809, http://gcn.gsfc.nasa.gov/gcn/gcn3/4809.gcn3
Foley, R. J., et al. 2003, PASP, 115, 1220
Friedman, A. S., & Bloom, J. S. 2005, ApJ, 627, 1
Fruchter, A. S., et al. 1999, ApJ, 519, L13
Fugazza, D., et al. 2006, Cent. Bur. Electron. Telegr., 410, 1
Galama, T. J., et al. 1998, Nature, 395, 670
Garnavich, P. M., et al. 2003, ApJ, 582, 924
Gehrels, N., et al. 2006, GCN Circ. 4787, http://gcn.gsfc.nasa.gov/gcn/gcn3/4787.gcn3
Ghirlanda, G., Ghisellini, G., & Firmani, C. 2005, MNRAS, 361, L10
Guenther, E. W., Klose, S., Vreeswijk, P., Pian, E., & Greiner, J. 2006, GCN Circ. 4863, http://gcn.gsfc.nasa.gov/gcn/gcn3/4863.gcn3
Hjorth, J., et al. 2003, Nature, 423, 847
Iwamoto, K., et al. 2000, ApJ, 534, 660
———. 1998, Nature, 395, 672
Kawabata, K. S., et al. 2003, ApJ, 593, L19
Kennea, G., Burrows, D. N., Cusumano, G., & Tagliaferri, G. 2006, GCN Circ. 4776, http://gcn.gsfc.nasa.gov/gcn/gcn3/4776.gcn3
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kewley, L. J., & Dopita, M. A. 2002, ApJS, 142, 35
Kosugi, G., et al. 2004, PASJ, 56, 61
Landolt, A. U. 1992, AJ, 104, 340
Lee, H., Grebel, E. K., & Hodge, P. W. 2003, A&A, 401, 141
Le Floc'h, E., et al. 2003, A&A, 400, 499
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Malesani, D., et al. 2004, ApJ, 609, L5
Marshall, F., Brown, P., Immler, S., & Cusumano, G.. 2006a, GCN Circ. 4800, http://gcn.gsfc.nasa.gov/gcn/gcn3/4800.gcn3
Marshall, G., Immler, S., & Cusumano, G. 2006b, GCN Circ. 4779, http://gcn.gsfc.nasa.gov/gcn/gcn3/4779.gcn3
Masetti, N., Palazzi, E., Pian, E., & Patat, F. 2006, GCN Circ. 4803, http://gcn.gsfc.nasa.gov/gcn/gcn3/4803.gcn3
Matheson, T., et al. 2003, ApJ, 599, 394
———. 2005, AJ, 129, 2352
Mazzali, P. A., & Pian, E. 2006, GCN Circ. 4812, http://gcn.gsfc.nasa.gov/gcn/gcn3/4812.gcn3
Mazzali, P. A., et al. 2003, ApJ, 599, L95
Mirabal, N., & Halpern, J. P. 2006a, GCN Circ. 4792, http://gcn.gsfc.nasa.gov/gcn/gcn3/4792.gcn3
———. 2006b, Cent. Bur. Electron. Telegr., 409, 1
Nousek, J., et al. 2006, GCN Circ. 4805, http://gcn.gsfc.nasa.gov/gcn/gcn3/4805.gcn3
Patat, F., et al. 2001, ApJ, 555, 900
Sakamoto, T., et al. 2006, GCN Circ. 4822, http://gcn.gsfc.nasa.gov/gcn/gcn3/4822.gcn3
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schmidt, G. D., Weymann, R. J., & Foltz, C. B. 1989, PASP, 101, 713
Soderberg, A., Berger, E., & Schmidt, B. 2006a, IAU Circ. 8674
———. 2006b, GCN Circ. 4804, http://gcn.gsfc.nasa.gov/gcn/gcn3/4804.gcn3
Sollerman, J., Östlin, G., Fynbo, J. P. U., Hjorth, J., Fruchter, A., & Pedersen, K. 2005, NewA, 11, 103
Stanek, K. Z. 2005, in AIP Conf. Proc. 752, Stellar Astrophysics with the World's Largest Telescopes, ed. J. Mikolajewska & A. Olech (New York: AIP), 142
Stanek, K. Z., et al. 2003, ApJ, 591, L17
———. 2005, ApJ, 626, L5
Tremonti, C. A., et al. 2004, ApJ, 613, 898
Woosley, S. E. 1993, ApJ, 405, 273