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GRB 060218/SN 2006aj: A GAMMA-RAY BURST AND PROMPT SUPERNOVA AT $z = 0.0335$

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ABSTRACT

We report the imaging and spectroscopic localization of GRB 060218 to a low-metallicity dwarf starburst galaxy at $z = 0.03345 \pm 0.00006$. In addition to making it the second nearest gamma-ray burst known, optical spectroscopy reveals the earliest detection of weak, supernova-like Si II near 5720 Å (∼0.1c), starting 1.95 days after the burst trigger. *UBVRI* photometry obtained between 1 and 26 days postburst confirms the early rise of supernova light, and suggests a short time delay between the gamma-ray burst and the onset of SN 2006aj if the early appearance of a soft component in the X-ray spectrum is understood as a "shock breakout." Together, these results verify the long-hypothesized origin of soft gamma-ray bursts in the deaths of massive stars.

Subject headings: gamma rays: bursts — supernovae: individual (SN 2006aj) — supernovae: general

Online material: color figure

1. INTRODUCTION

It is now accepted that the so-called long-soft ($\gtrsim$2 s) gamma-ray bursts (GRBs) accompany some core-collapse supernovae of Type Ic (Galama et al. 1998; Patat et al. 2001; Stanek et al. 2003; Hjorth et al. 2003). The collective evidence also lends credence to the collapsar model for GRBs, in which a relativistic jet breaks through and explodes a hydrogen-stripped Wolf-Rayet star (Woosley 1993; MacFadyen & Woosley 1999). Unfortunately, our understanding of these energetic explosions is still limited by the paucity of nearby ($z \lesssim 0.2$) GRBs with high-quality photometry and spectroscopy.

On UT 2006 February 18.149, the *Swift* Burst Alert Telescope (BAT) detected an unusually long duration high-energy event (Cusumano et al. 2006a). Its prompt gamma-ray light curve was soft, confined to the 15–50 keV band for the first 290 s (Barbier et al. 2006); this was followed by a spectrally harder (25–100 keV) 10 s "spike" that concluded with an exponential coda extending beyond $t \approx 2000$ s (Barthelmy et al. 2006). The odd behavior of this transient generated uncertainty as to its basic nature (Gehrels 2006 and references therein), and poor observing conditions on Kitt Peak prevented a quick resolution. However, the identification of an extended optical object at the precise position of the X-ray and optical transient (OT) in preburst observations of this field (Cool et al. 2006; Mirabal 2006) favored an extragalactic location. Ultimately, optical spectroscopic observations of the OT discovered by the *Swift* UV/Optical Telescope (Cusumano et al. 2006a) confirmed the low-redshift $z = 0.033$, extragalactic nature of this unusual GRB (Mirabal & Halpern 2006a), making it the second lowest burst redshift known to date after GRB 980425/SN 1998bw at $z = 0.0085$.

In this Letter we describe the identification of the GRB 060218 host galaxy and its redshift, together with photometry and spectroscopy that verify its origin in the explosion of a massive star, and discuss the implications of our results. We assume an $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ cosmological model, corresponding to a luminosity distance $D_L = 145$ Mpc at $z = 0.0335$ and an angular scale 0.658 kpc arcsec^{-1}.

2. OBSERVATIONS

Optical observations of GRB 060218 began at the MDM Observatory on February 19.146 UT using the 2.4 m telescope and RETROCAM, the Retractable Optical Camera for Monitoring, equipped with Sloan Digital Sky Survey (SDSS) filters (Morgan et al. 2005) and continued on February 20. Additional *UBVRI* photometric observations were carried out on the MDM 1.3 and 2.4 m telescopes using a SITe 2048 × 2048 thinned, back side–illuminated CCD on several nights from February 21 to March 16. All of the photometry was converted to a common *UBVRI* system using Landolt (1992) standard stars and corrected for Galactic extinction assuming $E(B - V) = 0.142$ from the dust maps of Schlegel et al. (1998). We note that this value is consistent with the extinction estimated from high-resolution spectra by Guenther et al. (2006) using the combined Na I D absorption-line equivalent widths from the Galaxy and GRB host. This uniform data set, listed in Table 1 and shown in Figure 1, can be fitted with a power-law decay plus a supernova (SN) light curve that will be described in more detail in the following section.

The position of the OT was measured with respect to the apparent host galaxy SDSS J032139.68+165201.7 using a set of unsaturated stars common to MDM and SDSS images. We find that the OT is centered on the compact galaxy to less than 0″.2 (130 pc) in each coordinate. This is to be compared with the galaxy's half-light radius, $r_{1/2} \approx 1''.5$ (1.0 kpc).

Spectra of GRB 060218 were obtained starting on February 20.097 UT with the Boller & Chivens CCD spectrograph (CCDS) mounted on the 2.4 m telescope. The setup used provides 3.1 Å pixel^{-1} dispersion and ≈8.2 Å resolution with a 1″ slit. The observations consisted of two 1800 s integrations under fair sky conditions. The spectra were processed using standard procedures in IRAF.[5] The wavelength scale was established by fitting a set of polynomials to Xe lamp spectra obtained immediately after each target exposure. The spectrophotometric standard star Feige 34 (Stone 1977), observed at comparable telescope pointing to the GRB, was used for flux calibration. Although no order-separating filter was used, we expect that

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TABLE 1
Optical Photometry of GRB 060218

Date (UT)	Filter	Magnitude	Date (UT)	Filter	Magnitude	Date (UT)	Filter	Magnitude
2006 Feb 22.173	*U*	17.10 ± 0.07	2006 Feb 20.208	*V*	17.89 ± 0.06	2006 Feb 25.114	*R*	16.96 ± 0.02
2006 Feb 23.210	*U*	16.87 ± 0.04	2006 Feb 21.196	*V*	17.73 ± 0.06	2006 Feb 26.112	*R*	16.82 ± 0.03
2006 Feb 25.119	*U*	16.82 ± 0.04	2006 Feb 22.186	*V*	17.50 ± 0.03	2006 Feb 27.162	*R*	16.84 ± 0.10
2006 Feb 26.154	*U*	16.92 ± 0.05	2006 Feb 23.196	*V*	17.30 ± 0.03	2006 Feb 28.136	*R*	16.83 ± 0.02
2006 Feb 28.160	*U*	16.93 ± 0.04	2006 Feb 25.112	*V*	17.10 ± 0.02	2006 Mar 2.140	*R*	16.83 ± 0.04
2006 Mar 2.153	*U*	17.32 ± 0.07	2006 Feb 26.140	*V*	17.01 ± 0.03	2006 Mar 3.098	*R*	16.85 ± 0.04
2006 Mar 4.106	*U*	17.62 ± 0.06	2006 Feb 27.167	*V*	17.00 ± 0.11	2006 Mar 4.094	*R*	16.88 ± 0.04
2006 Mar 6.135	*U*	17.98 ± 0.20	2006 Feb 28.168	*V*	16.93 ± 0.02	2006 Mar 6.113	*R*	16.90 ± 0.06
2006 Mar 16.111	*U*	19.96 ± 0.13	2006 Mar 2.143	*V*	16.97 ± 0.03	2006 Mar 16.106	*R*	17.60 ± 0.04
2006 Feb 20.214	*B*	18.08 ± 0.10	2006 Mar 3.102	*V*	17.04 ± 0.02	2006 Feb 20.191	*I*	17.65 ± 0.08
2006 Feb 22.169	*B*	17.79 ± 0.03	2006 Mar 4.097	*V*	17.09 ± 0.05	2006 Feb 21.172	*I*	17.82 ± 0.20
2006 Feb 23.202	*B*	17.66 ± 0.03	2006 Mar 6.118	*V*	17.25 ± 0.04	2006 Feb 22.177	*I*	17.36 ± 0.03
2006 Feb 25.109	*B*	17.47 ± 0.02	2006 Mar 13.112	*V*	17.86 ± 0.03	2006 Feb 23.100	*I*	17.24 ± 0.04
2006 Feb 26.126	*B*	17.44 ± 0.02	2006 Mar 16.108	*V*	18.07 ± 0.03	2006 Feb 25.116	*I*	16.86 ± 0.03
2006 Feb 27.173	*B*	17.37 ± 0.13	2006 Feb 19.146	*R*	17.25 ± 0.10	2006 Feb 26.102	*I*	16.81 ± 0.10
2006 Feb 28.015	*B*	17.47 ± 0.02	2006 Feb 19.230	*R*	17.34 ± 0.10	2006 Feb 27.158	*I*	16.74 ± 0.06
2006 Mar 2.147	*B*	17.66 ± 0.02	2006 Feb 20.162	*R*	17.76 ± 0.06	2006 Feb 28.134	*I*	16.77 ± 0.06
2006 Mar 3.105	*B*	17.78 ± 0.02	2006 Feb 20.168	*R*	17.76 ± 0.06	2006 Mar 2.130	*I*	16.70 ± 0.10
2006 Mar 4.100	*B*	17.89 ± 0.03	2006 Feb 20.191	*R*	17.77 ± 0.06	2006 Mar 3.089	*I*	16.72 ± 0.05
2006 Mar 6.124	*B*	18.19 ± 0.07	2006 Feb 20.240	*R*	17.78 ± 0.06	2006 Mar 4.091	*I*	16.65 ± 0.06
2006 Mar 13.114	*B*	19.20 ± 0.05	2006 Feb 21.180	*R*	17.78 ± 0.15	2006 Mar 6.109	*I*	16.73 ± 0.06
2006 Mar 16.109	*B*	19.58 ± 0.04	2006 Feb 22.161	*R*	17.40 ± 0.02	2006 Mar 13.109	*I*	17.09 ± 0.06
2006 Feb 20.162	*V*	17.84 ± 0.06	2006 Feb 23.192	*R*	17.22 ± 0.03	2006 Mar 16.105	*I*	17.17 ± 0.04

Note.—The host galaxy with $U = 20.10$, $B = 20.41$, $V = 20.09$, $R = 19.91$, and $I = 19.54$ was subtracted, and then remainders were corrected for Galactic extinction: $A_U = 0.77$, $A_B = 0.61$, $A_V = 0.47$, $A_R = 0.38$, and $A_I = 0.28$, respectively.

second-order contamination is less than 1.5% below 7000 Å (e.g., Izotov et al. 2001). Another set of spectra, consisting of three 720 s integrations, was obtained on March 17.12 UT using the Modular Spectrograph (ModSpec) on the 2.4 m telescope, which provides 2 Å pixel^{-1} dispersion and ≈3.6 Å resolution with a 1".1 slit. Similar reduction steps, plus correction for atmospheric absorption bands, were performed. Figure 2 shows the dereddened (Cardelli et al. 1989), wavelength- and flux-calibrated spectra of GRB 060218/SN 2006aj.

3. RESULTS

Strong, redshifted nebular emission lines identified in the spectrum are listed in Table 2. The fluxes are taken from the CCDS spectrum, while the more accurate wavelengths from the

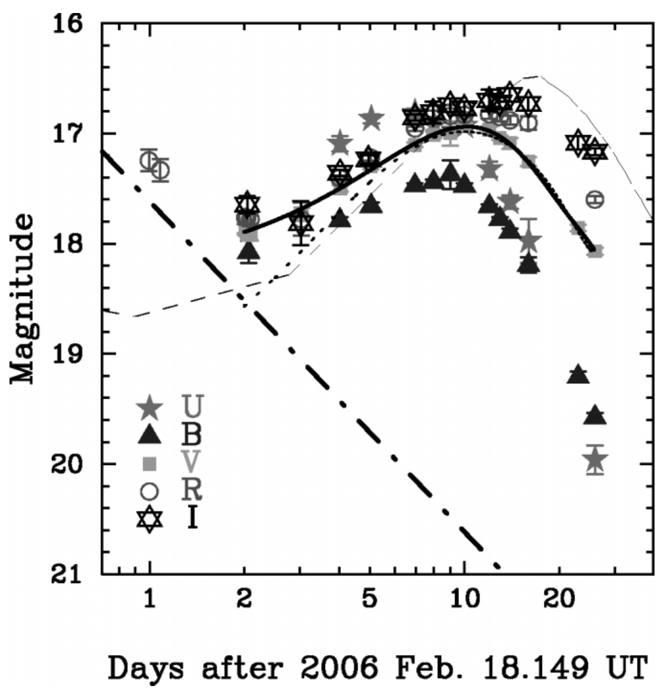

Fig. 1.—*UBVRI* data for GRB 060218, corrected for Galactic extinction and host galaxy contamination. The solid line is a fit to the *V*-band light curve. The dotted line is a fit to the *V*-band light curve after subtracting an $\alpha = 1.2$ power-law decay (dot-dashed line) as justified in the text. The dashed line is a template of the *V*-band light curve of SN 1998bw (Galama et al. 1998) shifted to $z = 0.0335$. [*See the electronic edition of the Journal for a color version of this figure.*]

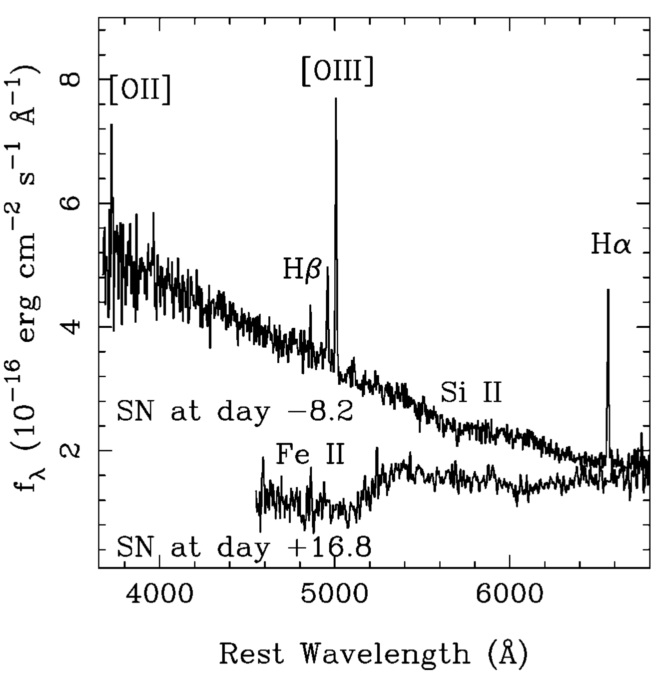

Fig. 2.—Spectra of GRB 060218 obtained on 2006 February 20.097 UT (1.95 days after the burst) and March 17.12 (27 days postburst). Days relative to supernova maximum are indicated. Starburst emission lines from the host galaxy were excised from the second spectrum. The first spectrum marks the earliest appearance of Si II near 5720 Å, while its continuum is reasonably well fitted by a spectral index $\beta = 0.1 \pm 0.3$ (see text). Photometry before and after the spectrum was taken (Table 1) is consistent with this spectral index.

TABLE 2
HOST GALAXY EMISSION LINES

Line λ_{air}	λ_{helio} (Å)	$F(\lambda)/F(\mathrm{H}\beta)$[a]
[O II] λ3727.5	3850.7[b]	2.61 ± 0.4
Hβ λ4861.33	5024.36	1.00 ± 0.3
[O III] λ4958.92	5124.84	2.03 ± 0.3
[O III] λ5006.85	5174.31	5.09 ± 0.6
Hα λ6562.79	6782.25	2.94 ± 0.3
[N II] λ6583.39	...	<0.08
[S II] λ6716.42	...	<0.65
[S II] λ6730.78	...	<0.54

[a] Flux relative to $F(\mathrm{H}\beta) = 9.94 \times 10^{-16}$ ergs cm^{-2} s^{-1}, corrected for Galactic extinction $E(B-V) = 0.142$.
[b] Poor wavelength calibration in this region.

ModSpec are listed. The weighted mean heliocentric redshift derived from the emission lines is $z = 0.03345 \pm 0.00006$, and the line widths are unresolved at the resolution of ≈160 km s^{-1}. The emission-line redshift is consistent with the Na I D absorption-line velocities from the host (Guenther et al. 2006), falling within the 20 km s^{-1} spread of the latter. The Balmer decrement indicates little or no intrinsic reddening. In addition, the earlier spectrum reveals a relatively blue continuum that is reasonably well fitted by a power law of the form $f_\nu \propto \nu^{-\beta}$ with spectral index $\beta = 0.1 \pm 0.3$ and by a broad P Cygni feature with the bottom of the absorption trough at ≈5720 Å rest wavelength.

We argue that this spectral feature corresponds to Si II λ6355 with velocity -31500 ± 9200 km s^{-1}. An identification with Na I D at -8700 km s^{-1}, or with He I λ5876 at even lower velocity, appears less likely when compared to the early-time optical spectra of Type Ic SNe (Patat et al. 2001). This detection signals the emergence of the supernova designated SN 2006aj (Masetti et al. 2006; Soderberg et al. 2006; Fugazza et al. 2006; Mirabal & Halpern 2006b; Fatkhullin et al. 2006; Mazzali & Pian 2006; Modjaz et al. 2006) and seals the connection between GRB 060218 and the explosion of a massive star. The weak Si II line, as well as a nearly featureless continuum at early times, are typical of Type Ic SN explosions lacking both a hydrogen and helium envelope (e.g., Filippenko 1997). SN 2006aj appears much bluer than the Type Ic SN 1998bw. The early spectral shape of SN 2006aj resembles more closely the Type Ic GRB 030329/SN 2003dh spectra obtained within a week of that burst (Stanek et al. 2003; Hjorth et al. 2003).

The emergence of a weak, broad Si II feature so soon after the *Swift* BAT localization implies that SN 2006aj began <1.95 days after the GRB 060218. This basic picture is confirmed by the flattening and rise in the optical light curve on 2006 February 21.181 UT (Fig. 1). To better constrain the SN contribution to the light curve, we subtracted the host galaxy contribution and, optionally, a power-law decay assumed to be from relativistic ejecta interacting with the circumburst medium. The host galaxy magnitudes were transformed from Cool et al. (2006), Adelman-McCarthy et al. (2006), and our own Landolt star calibrations. There is direct evidence that emission generated by the relativistic ejecta began on the first day after the trigger, when a temporal power-law index $\alpha \approx 1.2$ describes the X-ray observations (Cusumano et al. 2006b). Such decay is slightly steeper than a power-law index $\alpha \approx 0.7 \pm 0.3$ that can be fitted to our R-band measurements prior to February 21, but these are consistent because the optical band is already affected by the SN rise at this point.

Taking $\alpha \approx 1.2$ as an estimate for the early optical decay (the dot-dashed line in Fig. 1) and subtracting it and the contribution of the host galaxy will produce the residual V-band SN light curve shown as the dotted line in Figure 1. Allowing for uncertainties in the initial optical decay rate, which could be slower than in the X-ray, the SN rise is consistent with an origin at the GRB trigger time. Alternatively, if we ignore the R-band points obtained on February 19–20 and assume that the light curve is completely accounted for by the SN on February 21, we get a much flatter SN light curve (the solid line in Fig. 1). The latter model is less attractive, as it neglects the first 2 days of bright, decaying optical emission and points to a supernova time several days before the GRB.

For comparison we show a fit of the V-band light curve of SN 1998bw (Galama et al. 1998) shifted to $z = 0.0335$. Both the raw and modeled V-band light curves suggest that SN 2006aj reached maximum in V on 2006 February 28.3 UT (10.2 ± 0.3 days after the burst). The peak of SN 2006aj occurs earlier than in SN 1998bw and is more like the Type Ic SN 2002ap (Gal-Yam et al. 2002; Mazzali et al. 2002). The peak absolute magnitude of SN 2006aj is $M_V = -18.87$. Although it was much bluer than SN 1998bw early on, SN 2006aj's maximum is 0.53 mag fainter than SN 1998bw, which probably translates into $\lesssim 0.5\ M_\odot$ of ejected ^{56}Ni mass during the explosion (Iwamoto et al. 1998; Woosley et al. 1999).

At a redshift of $z = 0.0335$, the γ-ray fluence of GRB 060218 corresponds to isotropic energy $E_{\mathrm{iso}} = (6.2 \pm 0.3) \times 10^{49}$ ergs, and the peak luminosity is $L_p = (5 \pm 3) \times 10^{46}$ ergs s^{-1} (Sakamoto et al. 2006; Campana et al. 2006). This energy release is at least an order of magnitude lower than the average energy measured in long-duration GRBs and yet a factor of ~20 larger than the intrinsically weak GRB 980425/SN 1998bw (Galama et al. 1998). It is in fact comparable to the soft X-ray flash XRF 020903 (Sakamoto et al. 2006). In terms of X-ray emission, the isotropic luminosity of GRB 060218 at $t = 10$ hr is $L_X \sim 10^{43}$ ergs s^{-1} (Cusumano et al. 2006b). This is 10^3 times fainter than the sample of GRB X-ray luminosities culled by Berger et al. (2003). However, this strict comparison may not be meaningful, since it does not take into account the contribution from an earlier flaring period. In fact, a rough estimate of the X-ray fluence of GRB 060218 for the first orbit of *Swift* data (159–2770 s posttrigger) yields $\approx 2.3 \times 10^{49}$ ergs, a large fraction of the total.

Next, we examine the host galaxy of GRB 060218. The observed line ratios are typical of a high-excitation starburst galaxy. In particular, the measured Hα line flux, uncorrected for extinction at the host galaxy, implies a star formation rate (SFR) equivalent to ≈0.05–0.15 $M_\odot$ yr^{-1} (Kennicutt 1998). A similar computation of the SFR using [O II] yields 0.09 ± 0.05 $M_\odot$ yr^{-1}. We also find a good agreement with the SFR derived using an extrapolation of the UV continuum luminosity of the host galaxy as tabulated in Cool et al. (2006).

Turning our attention to host galaxy metallicity, we estimate relative abundances from intensities of [O II], Hβ, and [O III] (Table 2) by adopting the calibrations in Kobulnicky & Kewley (2004). Under this approximation, the metallicity is [O/H] $= -0.34 \pm 0.3$, assuming $\log(\mathrm{O/H})_\odot + 12 = 8.72$ (Allende Prieto et al. 2001). This value is slightly larger than the measurement for the XRF 031203 host (Prochaska et al. 2004), but it is still among the lowest observed for GRB hosts. We also estimate $M_B \approx -16.01$ for SDSS J032139.68+165201.7, which ranks at the bright end of Local Group dwarf galaxies (Mateo 1998).

4. DISCUSSION

Together, its energetics and host galaxy metallicity place GRB 060218 somewhere between GRB 980425/SN 1998bw (Galama et al. 1998) and XRF 031203 (Soderberg et al. 2004).

Most importantly, this event continues to shape a picture in which subluminous, subenergetic GRBs/supernovae born in low-metallicity, dwarf galaxies dominate the local ($z \lesssim 0.5$) population of GRB events (e.g., Soderberg et al. 2004). It remains to be seen whether this empirical result constitutes a selection effect (i.e., we are simply missing the analogs of faint explosions at higher redshifts) or whether the trend is indeed a real consequence of stellar and/or metallicity evolution over the ages (Ramirez-Ruiz et al. 2002b; Woosley & Janka 2005; Langer & Norman 2006). If the latter is correct, low-metallicity progenitors in the local universe may differ from GRB progenitors at higher redshifts.

It is notable that during the early, X-ray bright phase, the absorbing column density needed to fit the *Swift* X-ray spectrum, $N_{\rm H} = 6 \times 10^{21}$ cm^{-2} (Campana et al. 2006), is considerably greater than both the Galactic and host extinction derived from optical emission and absorption lines, as well as from the optical colors of the afterglow. The standard Galactic ratio $N({\rm H\ I} + {\rm H_2})/E(B-V) = 5.8 \times 10^{21}$ cm^{-2} mag^{-1} (Bohlin et al. 1978) predicts $E(B-V) \approx 1$, rather than the $E(B-V) \approx 0.17 \pm 0.03$ observed from the optical methods. Since "X-ray $N_{\rm H}$" is not really $N_{\rm H}$ but a proxy for the heavier elements that dominate X-ray photoelectric absorption, this implies a dust-deficient medium. The stellar wind of a Wolf-Rayet progenitor has enough column density to be the location of this excess photoelectric X-ray absorption.

Phenomenologically, GRB 060218 does share some properties with the "classical" high-redshift burst population, showing the canonical imprint of emission from a relativistic blast wave or jet running into circumstellar material ($\alpha \approx 1.2$) prior to the SN emergence. It also has extended prompt X-ray emission remarkably similar to the early X-ray light curves inferred from *Swift* X-Ray Telescope observations (Zhang et al. 2005). Based solely on the early results from GRB 060218, and using our sparse optical data before the SN rise, we cannot firmly distinguish among a relativistic jet afterglow, emission from a jet cocoon (Ramirez-Ruiz et al. 2002a), or decaying blackbody radiation associated with "shock breakout" (Campana et al. 2006). In spherical SN models, shock breakout refers to the first observable event after core collapse, and it will occur at $\Delta t \sim 1$ hr (Arnett 1996). But in the case of a highly asymmetric explosion accompanying a GRB, a narrow "jet breakout" can be observed, as well as a jet-driven shock emerging with different delays from around the stellar envelope.

5. CONCLUSIONS

We report the identification of GRB 060218 as the second nearest GRB known to date. Taken together, the emerging SN light curve, the development of a Si II feature, and the lack of hydrogen lines in the spectrum indicate that the progenitor was a massive star, most likely in the Wolf-Rayet family, that was stripped of its hydrogen and helium envelope prior to the explosion. The residual decay $\lesssim 2$ days after the burst suggests that a fraction of the early emission was created by a mildly relativistic blast wave or jet running into circumstellar material. Furthermore, the extrapolation of a derived SN 2006aj light curve back in time supports the idea that the GRB was nearly simultaneous with the massive core collapse that gave rise to the SN. Finally, the subenergetic nature of this nearby event and its location within a low-metallicity host galaxy highlight the possibility that the variety in massive stellar explosions is, in part, intrinsic to the metallicity of their progenitors.

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