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SN 2006aj AND THE NATURE OF LOW-LUMINOSITY GAMMA-RAY BURSTS

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ABSTRACT

We present SMARTS consortium optical/IR light curves of SN 2006aj, associated with GRB 060218. We find that this event is broadly similar to two previously observed events, SN 1998bw/GRB 980425 and SN 2003lw/GRB 031203. In particular, all of these events are greatly underluminous in gamma rays compared with typical long-duration GRBs. We find that the observation by *Swift* of even one such event implies a large enough true event rate to create difficulties in interpreting these events as typical GRBs observed off-axis. Thus, these events appear to be intrinsically different from and much more common than high-luminosity GRBs, which have been observed in large numbers out to a redshift of at least 6.3. The existence of a range of intrinsic energies of GRBs may present challenges to using GRBs as standard candles.

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

Online material: machine-readable table

1. INTRODUCTION

While some long-duration gamma-ray bursts (GRBs) are clearly associated with supernovae (SNe), a deeper understanding of the GRB-SN connection remains elusive. The GRB-SN link was first confirmed observationally with the detection of the low-redshift GRB 980425/SN 1998bw ($z = 0.0085$) (Galama et al. 1998). GRB 980425, however, was not a typical GRB; it was underluminous in gamma rays and had no detected optical afterglow (OAG). SNe were later associated with typical GRBs at cosmological redshifts (e.g., Bloom et al. 1999; Della Valle et al. 2003). However, no low gamma-ray luminosity event similar to GRB 980425/SN 1998bw was observed until GRB 031203. This burst was also orders of magnitude underenergetic and, despite its low redshift ($z = 0.1055$; Prochaska et al. 2004), was followed by only a dim OAG (Malesani et al. 2004). Follow-up observations of this burst detected a SN-like brightening (Cobb et al. 2004; Gal-Yam et al. 2004; Thomsen et al. 2004), and SN 2003lw was confirmed spectroscopically by Tagliaferri et al. (2004). The spectra of SN 2003lw were reminiscent of those of SN 1998bw (Malesani et al. 2004). The two SNe also had similar peak magnitudes, although SN 2003lw was somewhat brighter and evolved more slowly. Their light-curve shapes were also qualitatively different, with SN 1998bw climbing smoothly to peak while SN 2003lw experienced a broad plateau.

The low gamma-ray luminosity of GRB 980425 and GRB 031203 suggested that they might represent a new GRB category. Alternatively, they could be normal GRBs that appeared underluminous because their jetted emission was observed off-axis (e.g., Yamazaki et al. 2003; Ramirez-Ruiz et al. 2005). A comparison of the event rate of low-luminosity with typical-luminosity GRBs was warranted, but only a small and inhomogeneous sample of well-localized GRBs existed before *Swift*, as pre-*Swift* GRBs were detected using multiple instruments, each with unique sensitivity and sky coverage. *Swift* provides a large and homogeneous GRB sample that is well suited for rate calculations.

On 2006 February 18 at 03:34:30 UT, *Swift* detected a new low-luminosity event: GRB 060218 (Cusumano et al. 2006). This was an unusual GRB with weak gamma-ray emission lasting over 2000 s (Barthelmy et al. 2006). This burst was followed by an unusual OAG that brightened for 10 hr before decaying like a typical OAG (see, e.g., Marshall et al. 2006). This was the first *Swift* GRB to be associated with a SN: SN 2006aj. The SN was initially noted in spectral observations (Masetti et al. 2006) and then detected as an optical rebrightening (e.g., D'Avanzo et al. 2006; Ovaldsen et al. 2006). At $z = 0.033$, GRB 060218 is now the second-closest GRB with a measured redshift (Mirabal & Halpern 2006). This is the third example of a GRB-related SN in which the gamma rays are highly underluminous and the SN light curve is clearly distinct from the GRB's OAG. Hereafter, we will refer to these *long*-duration, *low-luminosity* events as L_3-GRBs.

SMARTS observations of SN 2006aj began on 2006 February 22 at 00:35 UT (Cobb & Bailyn 2006). We present optical/IR data obtained between 5 and 30 days following GRB 060218. Our homogeneous data demonstrate that the light curve of SN 2006aj is qualitatively similar to that of the pre-*Swift* L_3-GRB SNe 1998bw and 2003lw. We argue in § 4 that the detection of this single event in the *Swift* era already places strong constraints on the nature of L_3-GRBs.

2. OBSERVATIONS AND DATA REDUCTION

Our data were obtained using the ANDICAM instrument mounted on the 1.3 m telescope at Cerro Tololo Inter-American Observatory.[1] This telescope is operated as part of the Small and Moderate Aperture Research Telescope System (SMARTS) consortium.[2] Nightly imaging was obtained over 26 days with occasional interruptions for weather and equipment problems. The GRB/SN was only observable for a limited period of time immediately after twilight ($\lesssim$1 hr). Consequently, all observations were obtained at high air mass (sec $z \gtrsim 2$).

Each nightly data set consisted of six individual 360 s *I*-band observations obtained simultaneously with 30 dithered 60 s *J*-band images. The data were reduced in the same way as in Cobb et al. (2004). A few additional steps were added, including cosmic-ray removal in the *I*-band images using the L.A. Cosmic program[3] (van Dokkum 2001) and *I*-band fringe correction using an iterative masking technique. Some images were not included in the final frames because of excessive

[1] See http://www.astronomy.ohio-state.edu/ANDICAM.
[2] See http://www.astro.yale.edu/smarts.
[3] See http://www.astro.yale.edu/dokkum/lacosmic.

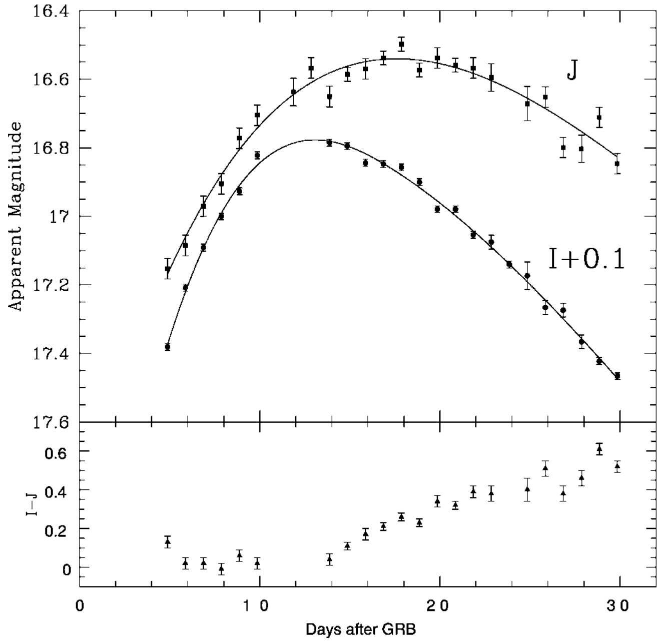

FIG. 1.—*Top*: *I*-band (*circles*) and *J*-band (*squares*) aperture-photometry light curve of the host+SN of GRB 060218. Values have been corrected for a Galactic foreground extinction of $A_V = 0.39$ mag. For clarity, the *I*-band points have been shifted by +0.1 mag. Error bars are photometric measurement errors and do not include possible systematic effects. The curves are fitted with second-order cubic splines. *Bottom*: $I-J$ color evolution. The combined light is observed to redden with time.

background due to twilight or because of telescope drift. Typically, the final frames were equivalent to 30 minutes of *I*- or *J*-band exposure time.

The relative magnitude of the SN plus host galaxy was determined by comparison with 11 and 3 on-chip nonvariable objects in *I* and *J*, respectively, using seeing-matched aperture photometry. Differential magnitudes were converted to apparent magnitudes by comparison, on photometric nights, with Landolt standard stars in the fields of RU 149 and PG 1047+003 (Landolt 1992) for the *I*-band images, and with three on-chip Two Micron All Sky Survey (2MASS) stars (Skrutskie et al. 2006) for the *J*-band images. The difference in air-mass value between the Landolt standard frames and science frames was corrected for using an extinction coefficient of 0.066 mag per air mass.

The light curves are shown in Figure 1, and the photometric data are summarized in Table 1. The error bars represent the photometric measurement error, which accurately reflects nightly variations in image quality but does not account for systematic measurement errors. In addition to the relative night-to-night uncertainty, there is a systematic error of 0.05 mag in *I* and *J* resulting from uncertainties in the photometric calibration.

3. RESULTS

Figure 1 shows that GRB 060218's optical and IR counterpart brightened for the first 2 weeks and then proceeded to gradually decay. This behavior is not consistent with that of a standard GRB OAG (e.g., Tagliaferri et al. 2005) but is reminiscent of the low-redshift events SNe 1998bw and 2003lw. Identification of this optical emission as a SN is possible from our data alone because of our dense observations and the object's particular transient behavior; spectral evidence obtained by other groups clearly supports our claim (Modjaz et al. 2006; Sollerman et al. 2006; Mirabal et al. 2006). The well-sampled nature of our observations allows us to determine an unambiguous time of peak brightness in *I* and *J*. This parameter will be important for determining the amount of mass ejected in the supernova explosion, thought this modeling is beyond the scope of this Letter. The position of peak brightness was determined by fitting second-order cubic splines to the data points, with errors derived from the formal χ^2 error on the fits in combination with the error on the measured magnitudes. The combination of the host galaxy and SN reaches a peak apparent magnitude in *I* of 16.91 ± 0.05 mag after $13.1^{+2.1}_{-1.9}$ days and in *J* of 16.65 ± 0.06 mag after $17.6^{+3.5}_{-3.2}$ days. The rest-frame time to peak is, therefore, approximately 12.7 days in *I* and 17.0 days in *J*.

The Galactic extinction corrections along the line of sight to the host galaxy are taken to be $A_I = 0.23$ mag and $A_J = 0.11$ mag, assuming the Galactic extinction curves of Cardelli et al. (1989) and a measured reddening value of $E(B-V) = 0.127$ mag (Guenther et al. 2006). The preburst Sloan Digital Sky Survey model magnitude of the host galaxy is $i = 19.805 \pm 0.041$ mag, not corrected for Galactic extinction (Adelman-McCarthy et al. 2006). Using the transformation equations derived by R. Lupton,[4] this corresponds to $I = 19.368 \pm 0.047$ mag. The peak absolute magnitude of the supernova is therefore $M_I = -19.02 \pm 0.09$ mag. No *k*-correction has been applied, but this should result in minimal error because of the low redshift of the burst. A correction of −0.04 mag was applied to account for spectral stretching. The exact preburst *J* magnitude of the host is unknown, as the host galaxy is too dim to appear in the 2MASS catalog. Our observations indicate the host galaxy must have a *J* magnitude fainter than 18. Assuming a range of host magnitudes from 18 to 20, the peak absolute magnitude of the supernova in *J* is approximately $M_J = -19.1 \pm 0.2$ mag.

Note that 2006aj clearly peaks later in *J* than in *I*. This later peak at redder wavelengths follows the trend seen in SN 1998bw, which, in the rest frame, peaked 1.6 days earlier in *V* than in *I*. The rest-frame *V*-band peak of SN 2006aj occurred at approximately 9.7 days (Modjaz et al. 2006), which is 2.9 days prior to the *I*-band peak. Likewise, SN 2003lw peaked in *V* at ∼18 days (Malesani et al. 2004) and in *I* at ∼23 days (Cobb et al. 2004; Malesani et al. 2004). The combined light of the galaxy and the SN reddens from $I-J = 0.0$ mag during the first week to $I-J = 0.6$ mag for the last few observations. This is a stronger evolution in $I-J$ color than experienced by either SN 1998bw or SN 2003lw, whose $I-J$ colors in the first month only changed by about 0.3 mag (Gal-Yam et al. 2004). This comparison is complicated, however, by the unknown intrinsic $I-J$ color of the host galaxy of SN 2006aj.

TABLE 1
PHOTOMETRY OF SN 2006aj IN THE HOST GALAXY OF GRB 060218

Days after GRB[a]	*I* Magnitude[b]	*J* Magnitude[b]
4.88	17.51 ± 0.01	17.26 ± 0.03
5.87	17.34 ± 0.01	17.20 ± 0.03
6.87	17.22 ± 0.01	17.08 ± 0.03

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 2006 February 18, 03:34:30 UT.
[b] These values have not been corrected for Galactic extinction. There is an additional uncertainty of 0.05 mag in the transformation of relative to apparent magnitudes.

[4] See http://www.sdss.org/dr4/algorithms/sdssUBVRITransform.html.

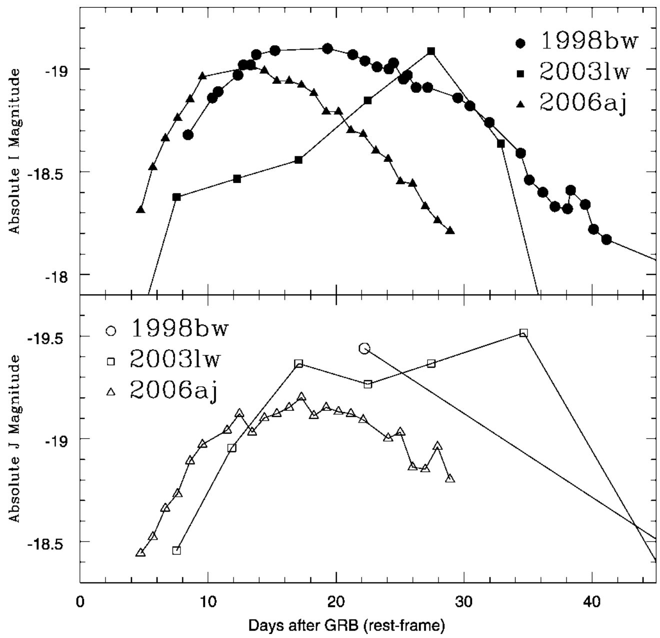

FIG. 2.—Absolute magnitude light curves of SNe 1998bw (*circles*), 2003lw (*squares*), and 2006aj (*triangles*) in *I* (*top*) and *J* (*bottom*). The SN 2003lw data have been binned in intervals of 5 days. The apparent *J*-band host galaxy magnitude of SN 2006aj is assumed to be 19 mag. SN 2003lw may be shifted by about −0.5 mag if a stronger line-of-sight extinction is assumed.

4. DISCUSSION

Our data, together with those of Modjaz et al. (2006), Sollerman et al. (2006), and Mirabal et al. (2006), show that GRB 060218 is the third detected GRB to be followed by a dominant SN. With such a small sample being used to extrapolate the characteristics for an entire category, it is important to collect homogeneous and detailed observations over a wide range of wavelengths. Our data provide dense IR coverage, which extends the total SN 2006aj data set out to redder bands than reported thus far. It is instructive to compare all three cases in which L_3-GRBs have been detected, each of which was followed by a Type Ic SN: 1998bw, 2003lw, and 2006aj (see Fig. 2). We note that the limits on observing L_3-GRB events are more stringent than those on observing the associated SNe, so it is unlikely that GRBs for which no optical counterpart are observed are of this character. The properties of these three events are shown in Table 2. All three SNe are very similar in peak brightness, though 2003lw may be half a magnitude brighter than the others. The biggest difference between the bursts is their rise times, with 2006aj peaking the fastest and 2003lw taking the longest time to peak. The rest-frame photon energy at which the GRB spectrum peaks ($E_{p,i}$) appears to increase with increasing SN rise time.

As discussed in § 1, it would be instructive to compare the frequency of these L_3 bursts with that of high-luminosity bursts using the homogeneous *Swift* data set. Such a comparison is now possible, since GRB 060218 is the first *Swift*-detected burst that falls in the category of low-luminosity GRBs associated with Type Ic SNe. The low observed fluxes and redshifts of L_3-GRBs suggest that the underlying rate of L_3-GRB events may be quite high (see also Pian et al. 2006; Soderberg et al. 2004), since the volume in which these sources can be observed is much smaller than that of typical GRBs. The ratio of the event rate of L_3-GRBs to ordinary long-duration GRBs is expected to be

$$\frac{R_{\rm int,L_3}}{R_{\rm int,GRB}} = \frac{R_{\rm obs,L_3}}{R_{\rm obs,GRB}}\left(\frac{D_{c,\rm GRB}}{D_{c,\rm L_3}}\right)^3,$$

where $R_{\rm int}$ denotes the true rate per comoving volume of the two kinds of events, $R_{\rm obs}$ is the observed event rate seen by a given experiment, and D_c is the comoving radial distance out to which the events could be observed by that experiment. In the case of *Swift*, the limiting volume in which L_3-GRBs are observable is so small that the observation of even one of these events implies an extremely high ratio of true rates.

Specifically, GRB 060218 would not have triggered the BAT event monitor if it had been ∼2 times fainter, which corresponds to a maximum redshift of $z = 0.046$. By contrast, the 31 high-luminosity, long-duration *Swift* GRBs that have measured redshifts have an average of $z = 2.6$. Many of these bursts would have been detected even if they had occurred at $z \gtrsim 6$. We will take a conservative approach, however, and assume that most of these bursts would not have been detected had they been at extreme redshifts and adopt $z = 2.6$ as the redshift below which the high-luminosity GRB samples are complete. Assuming the

TABLE 2
GRB/SN PROPERTIES

Property	GRB 980425/ SN 1998bw	SN 2003lw	GRB 060218/ SN 2006aj
Redshift	0.0085	0.1055	0.033
Fluence (10^{-6} ergs cm^{-1})	2.8 ± 0.5[a]	2.0 ± 0.4[b]	6.8 ± 0.4[c]
Total duration (s)	∼40	∼40	>2000
$E_{p,i}$ (keV)	55 ± 15[d]	158 ± 51[d]	<10[e]
$E_{\rm iso}$ (1×10^{50} ergs)[f]	0.010 ± 0.002[d]	1.0 ± 0.4[d]	0.65 ± 0.15[e]
I-band $T_{\rm peak}$ (days)[g]	17.7 ± 0.3[h]	18–28[i]	$12.7^{+2.0}_{-1.8}$
Peak M_I (mag)	−19.27 ± 0.05[h]	−19.0 to −19.7[i]	−19.02 ± 0.09
$I-J$ SN color, $\sim T_{{\rm peak},I}$	0.5[l]	∼0.4[i]	∼0.0[m]

[a] From 40 to 700 keV (Pian et al. 2000).
[b] From 20 to 200 keV (Sazonov et al. 2004).
[c] From 15 to 150 keV (Sakamoto et al. 2006).
[d] Amati 2006.
[e] Amati et al. 2006.
[f] Rest-frame 1–10,000 keV, assuming $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.7$, and $\Omega_m = 0.3$.
[g] In the rest frame.
[h] Galama et al. 1998.
[i] Exact value depends strongly on extinction assumptions (Cobb et al. 2004; Gal-Yam et al. 2004; Malesani et al. 2004; Thomsen et al. 2004).
[l] At ∼22 days postburst (Patat et al. 2001).
[m] Assuming a *J*-band host magnitude of 19.

concordance cosmology of $\Omega_\Lambda = 0.73$, $\Omega_m = 0.27$, and a Hubble constant of 71 km s^{-1} Mpc^{-1}, the ratio of the comoving radial distance cubed for these two events is 3.1×10^4. Assuming that the ratio of rates is equal to the number of long-duration GRB events observed to date (one L_3-GRB per about 100 GRBs), we find a true event ratio of 3×10^2. In the near future, thanks to *Swift*, the cosmological GRB sample may be complete out to at least a redshift of $z \sim 5$. For this volume, the true event ratio increases by a factor of ∼2. If the current highest GRB redshift measurement, $z = 6.3$, is representative of the redshift out to which we have a complete sample, then the true event ratio is $\sim 10^3$. We also note that we are assuming a constant GRB rate per unit time. If, instead, the rate scales with the star formation rate (e.g., Natarajan et al. 2005), then the relevant ratio would be higher still.

These event ratios provide a constraint on the origins of L_3-GRBs. One explanation of these events is that they are standard GRBs observed off-axis (e.g., Yamazaki et al. 2003; Ramirez-Ruiz et al. 2005). This is an attractive option, as it accounts for all long-duration GRBs using a "unified model," with observed differences attributed only to viewing angle. However, this scenario implies a maximum true rate ratio, which would be generated if the L_3-GRBs could be observed from any angle. This upper limit is $2\pi/\theta_j^2$, where θ_j^2 is the jet opening solid angle of a typical GRB (in steradians). Jet breaks observed in X-ray/optical afterglow light curves constrain the jet opening angle to ∼10° (e.g., Frail et al. 2001), so we infer a maximum true rate ratio of 65 in this model. This ratio is a factor of 5 lower than the ratio of 3×10^2, which we inferred for $z = 2.6$, and lower by ∼20 than for $z = 6.3$.

Since *Swift* has observed only one L_3-GRB, the underlying event rate remains uncertain; GRB 060128/SN 2006aj could have been a serendipitous event. From Poisson statistics, the 90% lower confidence limit of the true event rate is an order of magnitude lower than assumed above, which implies that the off-axis scenario is still acceptable, provided one assumes a limit of $z = 2.6$ and a constant GRB rate. If *Swift* detected a second L_3-GRB, the off-axis scenario would become significantly less probable. Such a Poissonian analysis addresses the question "given an event rate, what is the probability of seeing an event," whereas in this case one might more appropriately ask the Bayesian question "having seen an event, what is the probability of a given event rate?" Assuming a uniform prior on the distribution of event rates (an assumption for which there is no real basis), we find that the off-axis scenario is implausible at the 98% level. Of course, the undetermined luminosity function of GRBs could complicate this calculation, as could cosmic evolution of the GRB source population.

At face value, however, the above calculation of the event rate suggests that there is a category of GRB events that is intrinsically different from that of typical GRBs. Several suggestions have been made for how these differences can be accounted for, including the possibility that the gamma rays are produced in supernova shock breakout (Matzner & McKee 1999; Tan et al. 2001) or "failed collapsars" in which highly relativistic jets fail to develop because of baryon loading (Woosley & MacFadyen 1999). The orientation-corrected energies of GRBs have been claimed to be constant at $\sim 10^{51}$ ergs (Frail et al. 2001). However, if intrinsically low-energy GRBs exist as a separate population, efforts to use GRBs as standard candles (e.g., Lazzati et al. 2006; Ghirlanda et al. 2004) may be compromised.

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