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THE OPTICAL/NEAR-INFRARED LIGHT CURVES OF SN 2002ap FOR THE FIRST 1.5 YEARS AFTER DISCOVERY

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ABSTRACT

Late-time *BVRIJHK* photometry of the peculiar Type Ic SN 2002ap, taken between 2002 June 12 and 2003 August 29 with the MAGNUM Telescope, is presented. The light-curve decline rate is derived in each band, and the color evolution is studied through comparison with nebular spectra and with SN 1998bw. Using the photometry, the OIR bolometric light curve is built, extending from before light maximum to day 580 after explosion. The light curve has a late-time shape strikingly similar to that of the hypernova SN 1998bw. The decline rate changes from 0.018 mag day^{-1} between days 130 and 230 to 0.014 mag day^{-1} between days 270 and 580. To reproduce the late-time light curve, a dense core must be added to the one-dimensional hypernova model that best fits the early-time observations, bringing the ejecta mass from 2.5 to 3 $M_{\odot}$ without much change in the kinetic energy, which is 4×10^{51} ergs. This is similar to the case of other hypernovae and suggests asymmetry. A large *H*-band bump developed in the spectral energy distribution after ~day 300, probably caused by strong [Si I] 1.646 and 1.608 μm emissions. The near-infrared flux contribution increased simultaneously from <30% to >50% at day 580. The near-infrared light curves were compared with those of other Type Ib/c supernovae, among which SN 1983I seems similar to SN 2002ap both in the near-infrared and in the optical.

Subject headings: supernovae: general — supernovae: individual (SN 2002ap)

1. INTRODUCTION

There is growing interest in Type Ib/c supernovae (SNe) following the discovery of a subclass that display very broad-lined spectra, indicating the existence of ejecta expanding with velocity >0.1*c*. Models of the optical spectra and the light curves (LCs) of this high-velocity subclass, also called hypernovae (HNe; e.g., Nomoto et al. 2004), have concluded that these are the explosions of massive C+O stars, producing up to 10 times the kinetic energy of normal core-collapse SNe (e.g., Iwamoto et al. 1998, 2000; Mazzali et al. 2003; Deng et al. 2005). It is unclear why some HNe are apparently associated with γ-ray bursts (GRBs), i.e., SN 1998bw and GRB 980425, (Galama et al. 1998), SN 2003 dh and GRB 030329 (Stanek et al. 2003), and SN 2003lw and GRB 031203 (Malesani et al. 2004), while others are not.

The Type Ic SN 2002ap, discovered in M74 (Nakano et al. 2002), is one of the nearest SNe in recent years. Its host galaxy has a distance modulus of only $29.5^{+0.1}_{-0.2}$ (Sharina et al. 1996; Sohn & Dvidge 1996; see also Hendry et al. 2005 for the latest review). Takada-Hidai et al. (2002) measured the total extinction toward the SN with a high-resolution spectrum and concluded that $E(B-V) = 0.09 \pm 0.01$. We adopt these values in this paper.

Early-time optical spectroscopy and photometry was published by Mazzali et al. (2002), Gal-Yam et al. (2002), Kinugasa et al. (2002), Foley et al. (2003), Pandey et al. (2003a), Vinkó et al. (2004), and others. Most authors emphasized the spectral similarity to the broad-lined SN 1998bw and SN 1997ef. The early-time LC was much broader than that of the normal Type Ic SN 1994I, but it was significantly fainter than that of SN 1998bw and peaked earlier.

Yoshii et al. (2003, hereafter Paper I) presented early-time near-infrared (NIR) and optical photometry, obtained with the MAGNUM Telescope. Using the *UBVRIJHK* photometry, they built a well-sampled optical-infrared (OIR) bolometric LC for SN 2002ap. NIR photometry has also been reported by Nishihara et al. (2002) and Mattila et al. (2002). Gerardy et al. (2004) described the evolution of NIR spectra, which were dominated by lines of intermediate-mass elements (see also Danziger et al. 2002).

Mazzali et al. (2002) modeled the early-time optical spectra and bolometric LC using one-dimensional codes. They concluded that SN 2002ap was the energetic explosion of a C+O star, having evolved from a star of 20–25 $M_{\odot}$ on the main sequence, and that it ejected ~2.5 $M_{\odot}$ material with a kinetic energy of $\sim 4 \times 10^{51}$ ergs, including ~0.07 $M_{\odot}$ ^{56}Ni. This places SN 2002ap at the low-mass, low-energy end of hypernovae. They also constrained the explosion date to MJD 52300.0 ± 0.5 days. We use the explosion date as the reference point for any SN epoch in this paper. Based on observed limits in prediscovery images, Smartt et al. (2002) argued that the progenitor was either a single W-R star of main-sequence mass <40 $M_{\odot}$ or more likely part of an interacting binary.

SN 2002ap was also monitored in the radio (Berger et al. 2002; Soderberg et al. 2006), X-rays (Sutaria et al. 2003; Soria

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et al. 2004), and UV (Soria & Kong 2002). Berger et al. (2002) estimated quite a small energy in any relativistic material from the faintness of the radio. They addressed the material with velocities larger than the shock velocity ($\sim$0.3c). Therefore, their results do not contradict the high energy obtained in the one-dimensional model for the bulk SN ejecta by Mazzali et al. (2002), whose ejecta velocity distribution has a cutoff at 70,000 km s^{-1}. As a possible confirmation of this result, the shock velocity derived by Björnsson & Fransson (2004) from models of the radio and X-ray observations was also $\sim$70,000 km s^{-1}.

SN 2002ap was not apparently associated with a GRB (Hurley et al. 2002). However, Kawabata et al. (2002) discovered a polarized spectrum component that resembled the total flux spectrum, but redshifted by $z \sim 0.3$ (see also Leonard et al. 2002; Wang et al. 2003). They proposed that this component is due to scattering from jet material. Totani (2003) further suggested that the jet may be too baryon-contaminated to trigger a GRB and that it was expanding almost freely and hence was radio-quiet. Tominaga et al. (2004) reproduced a bump in the LC of the XRF 030723 afterglow with a SN-2002ap–like LC.

SN 2002ap was monitored into the late nebular phase. Foley et al. (2003) published optical photometry covering from 2002 June to 2002 December and spectroscopy continuing to 2003 February. The spectra show unusually strong and sharp-peaked [O I] and Mg I] emission lines (see also Leonard et al. 2002). Late-time spectroscopy was also obtained by other observers (Y. Qiu 2002, K. Kawabata 2002, and S. B. Pandey 2003, private communications), and late-time photometry by Vinkó et al. (2004) and Doroshenko et al. (2003).

It is also important to have intensive late-time NIR observations of Type Ib/c SNe. As demonstrated in the case of SN 1998bw (Patat et al. 2001; Sollerman et al. 2002), the NIR contribution to the total flux is quite large, in particular at late times. Late-time NIR observations may also reveal molecule and dust formation, if any exists (e.g., Gerardy et al. 2004). However, few Type Ib/c SNe have been observed at late phases in the NIR. For SN 2002ap, the only late-time NIR observation published so far is a spectrum taken in 2002 August (Gerardy et al. 2004).

In this paper we report on *BVRIJHK* imaging photometry obtained for SN 2002ap between 2002 June 12 and 2003 August 29, completing the 1.5 yr follow-up project with the MAGNUM Telescope (see also Paper I). We describe the observations and data reduction and present our multicolor LCs in § 2. An OIR bolometric LC is then constructed using the photometry. In § 3 we discuss the bolometric LC, analyze the evolution of the spectral energy distribution (SED), compare the late-time NIR LCs with those of other Type Ib/c SNe, and present one-dimensional models for the bolometric LC.

2. IMAGING PHOTOMETRY

2.1. *Observations and Data Reduction*

Optical (Johnson-Cousins *BVRI*) and NIR (*JHK*) imaging photometry of SN 2002ap ($\alpha = 01^{\mathrm{h}}36^{\mathrm{m}}23^{\mathrm{s}}.85$, $\delta = +15^\circ 45' 13''.2$ [J2000.0]) was carried out using the MAGNUM 2 m telescope at the summit of Haleakala on the island of Maui, Hawaii (Yoshii 2002). The multicolor imaging photometer mounted at the bent-Cassegrain focus has an SITe 1024 × 1024 pixel CCD with a scale of $0''.277$ pixel^{-1}, for which the light is effectively received in a field of view of 430 × 430 pixel CCD or $119'' \times 119''$, and also has an SBRC 256 × 256 pixel InSb with a scale of $0''.346$ pixel^{-1} yielding a field of view of $88''.5 \times 88''.5$. A dichroic beam splitter enables simultaneous imaging through optical (*UBVRI*) and NIR (*ZJHK′KL′*) filters (Kobayashi et al. 1998b).

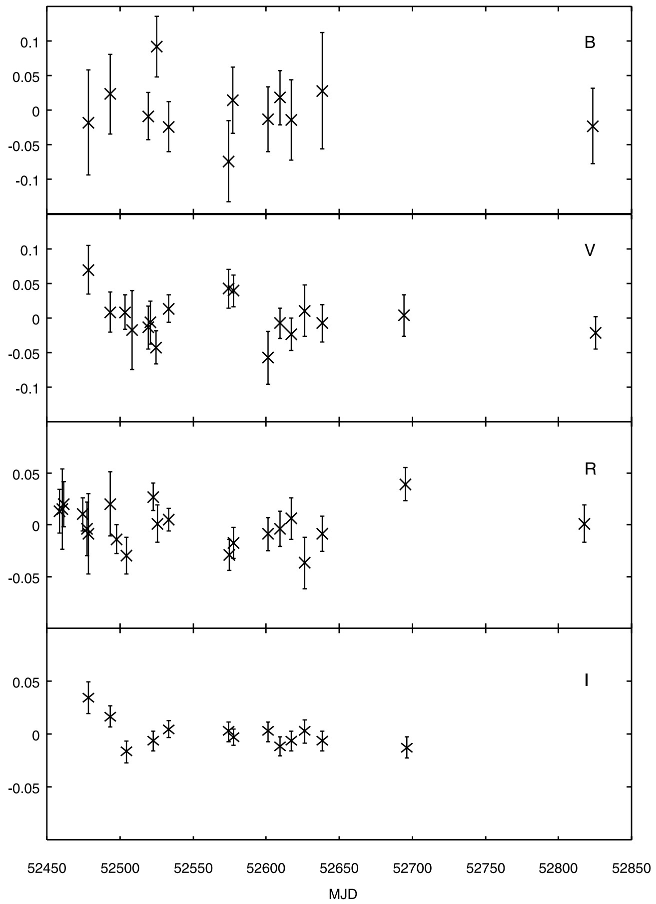

FIG. 1.—Difference between observed magnitudes of two reference stars [$\Delta m \equiv m(\mathrm{A}) - m(\mathrm{B})$] in the *BVRI* bands for MAGNUM observations after 2003 July. The mean difference $\langle \Delta m \rangle$ is shifted to zero. Error bars are estimated from photon statistics. The standard deviation of data distribution and mean error from photon statistics are 0.042/0.053 (*B*), 0.032/0.030 (*V*), 0.020/0.020 (*R*), and 0.014/0.010 (*I*). The computed reduced χ^2 values were 0.67 for *B*, 1.11 for *V*, 1.23 for *R*, and 1.33 for *I*.

The observations were scheduled by the MAGNUM scheduler (Kobayashi et al. 1998a), except for the solar conjunction from March to June in 2003. Telescope dithering was performed with $6''$ or $10''$ steps primary for *J*, *H*, and *K*. The typical exposure time for one step was 190 s for *B*, 95 s for *V*, 65 s for both *R* and *I*, 60 s for *J*, and 30 s for both *H* and *K*. As SN 2002ap faded, the number of dithering steps was increased from 6 to 12. The typical seeing size of the stellar image was $1''.0$–$1''.6$ in *V* and $0''.85$–$1''.4$ in *K*. Dome-flat images for *BVRIJHK* and NIR dark images were obtained at the end of each night.

Image reduction was performed using our package of IRAF-based[10] automated reduction software (MAGRED), which includes the standard corrections for bias and flat field frames. For more details see Paper I.

Two reference stars, A and B, were observed in the same frame of SN 2002ap for differential photometry. One reference star (A, $\alpha = 01^{\mathrm{h}}36^{\mathrm{m}}19^{\mathrm{s}}.49$ and $\delta = +15^\circ 45' 20''.8$ [J2000.0]) was used for *BVRI* as in Paper I. The other reference star (B, $\alpha = 01^{\mathrm{h}}36^{\mathrm{m}}20^{\mathrm{s}}.32$ and $\delta = +15^\circ 44' 54''.3$) was used for *JHK*. In order to calibrate the magnitude of star B, NIR standard stars (Hunt et al. 1998) were also observed, whenever possible, either before or after the observation of SN 2002ap. The median magnitudes and

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TABLE 1

Data of Light Curves of SN 2002ap

UT	MJD	m_B	m_V	m_R	m_I	m_J	m_H	m_K	Weather
Jun 12.61	52437.61	...	16.15 ± 0.02	...	...	...	...	14.98 ± 0.04	Clear
Jun 13.60	52438.60	16.75 ± 0.03	...	...	...	...	14.93 ± 0.05	...	Clear
Jun 14.60	52439.60	...	...	15.43 ± 0.02	...	15.75 ± 0.03	...	...	Clear
Jun 16.60	52441.60	...	...	...	15.10 ± 0.02	...	...	...	Clear
Jun 18.60	52443.60	...	...	...	15.14 ± 0.02	...	15.01 ± 0.05	...	Clear
Jul 3.56	52458.56	17.07 ± 0.05	...	15.70 ± 0.02	...	16.17 ± 0.04	...	15.49 ± 0.06	Thin cloud
Jul 5.60	52460.60	...	...	15.72 ± 0.02	...	...	...	...	Thin cloud
Jul 6.55	52461.55	...	...	15.74 ± 0.02	...	...	...	15.53 ± 0.08	Cloudy
Jul 19.56	52474.56	...	...	15.94 ± 0.02	...	...	...	...	Clear
Jul 22.56	52477.56	...	...	15.98 ± 0.02	...	...	...	...	Clear
Jul 23.51	52478.51	17.42 ± 0.03	17.00 ± 0.02	16.01 ± 0.02	15.75 ± 0.02	16.51 ± 0.03	15.74 ± 0.06	15.84 ± 0.06	Clear
Aug 7.47	52493.47	17.71 ± 0.04	17.36 ± 0.02	16.28 ± 0.02	16.04 ± 0.02	16.81 ± 0.04	16.00 ± 0.07	16.03 ± 0.09	Thin cloud
Aug 11.59	52497.59	...	...	16.34 ± 0.02	...	16.80 ± 0.04	...	...	Thin cloud
Aug 17.61	52503.61	...	17.59 ± 0.02	...	...	...	16.14 ± 0.06	...	Thin cloud
Aug 18.44	52504.44	...	...	16.45 ± 0.02	16.24 ± 0.02	17.05 ± 0.04	...	...	Clear
Aug 22.54	52508.54	...	17.64 ± 0.03	16.51 ± 0.02	16.29 ± 0.02	16.87 ± 0.04	16.22 ± 0.07	...	Cloudy
Sep 2.44	52519.44	18.16 ± 0.05	17.89 ± 0.02	...	...	...	16.36 ± 0.07	16.74 ± 0.08	Clear
Sep 3.61	52520.61	...	17.90 ± 0.02	...	...	...	16.43 ± 0.07	...	Thin cloud
Sep 5.59	52522.59	...	...	16.73 ± 0.02	16.54 ± 0.02	17.22 ± 0.04	...	...	Thin cloud
Sep 7.61	52524.61	...	18.02 ± 0.02	...	...	...	16.56 ± 0.07	...	Cloudy
Sep 8.41	52525.41	18.25 ± 0.05	...	16.77 ± 0.02	...	17.41 ± 0.07	...	16.98 ± 0.13	Cloudy
Sep 16.54	52533.54	18.41 ± 0.05	18.15 ± 0.02	16.91 ± 0.02	16.73 ± 0.02	17.42 ± 0.04	16.57 ± 0.06	17.07 ± 0.10	Clear
Oct 27.52	52574.52	19.12 ± 0.10	18.86 ± 0.03	17.59 ± 0.03	17.41 ± 0.03	17.93 ± 0.07	17.08 ± 0.08	18.24 ± 0.27	Clear
Oct 30.45	52577.45	19.11 ± 0.09	18.92 ± 0.04	17.61 ± 0.02	17.46 ± 0.04	17.88 ± 0.06	17.09 ± 0.08	17.96 ± 0.19	Thin cloud
Nov 23.22	52601.22	19.49 ± 0.13	19.31 ± 0.05	17.99 ± 0.03	17.94 ± 0.04	...	17.21 ± 0.07	...	Clear
Dec 1.39	52609.39	19.67 ± 0.15	19.40 ± 0.05	18.12 ± 0.03	18.06 ± 0.04	...	17.29 ± 0.07	...	Clear
Dec 9.35	52617.35	19.75 ± 0.15	19.58 ± 0.06	18.26 ± 0.03	18.19 ± 0.04	...	17.32 ± 0.07	...	Clear
Dec 18.37	52626.37	19.91 ± 0.19	19.66 ± 0.09	18.38 ± 0.04	18.34 ± 0.05	18.55 ± 0.08	...	...	Clear
Dec 30.37	52638.37	20.03 ± 0.20	19.85 ± 0.08	18.62 ± 0.03	18.47 ± 0.06	...	17.38 ± 0.08	...	Clear
Feb 11.22	52681.22	...	...	...	...	...	...	<19.7	Clear
Feb 23.22	52693.22	20.99 ± 0.42	...	...	...	...	...	...	Clear
Feb 24.23	52694.23	...	20.49 ± 0.11	...	...	...	...	...	Clear
Feb 25.23	52695.23	...	...	19.60 ± 0.06	...	...	...	...	Clear
Feb 26.23	52696.23	...	...	...	19.50 ± 0.12	...	...	...	Clear
Mar 11.21	52709.21	...	...	...	...	...	17.89 ± 0.13	...	Clear
Mar 12.22	52710.22	...	...	...	...	19.16 ± 0.22	...	...	Clear
Jun 27.62	52817.62	...	...	21.26 ± 0.22	...	...	...	...	Clear
Jul 3.60	52823.60	22.80 ± 1.36	...	...	...	...	...	...	Clear
Jul 5.60	52825.60	...	21.75 ± 0.31	...	...	...	18.80 ± 0.21	...	Clear
Aug 15.49	52866.49	...	...	...	<21.5	...	...	...	Thin cloud
Aug 28.50	52879.50	...	...	...	...	<21.2	19.83 ± 0.34	...	Clear
Aug 29.50	52880.50	...	...	...	...	...	...	<19.9	Clear

the number of calibrations for star B in the InSb frame are $J(6) = 15.69 \pm 0.02$, $H(6) = 15.11 \pm 0.05$, and $K(6) = 14.86 \pm 0.03$.

A variability check was made for stars A and B by increasing the total exposure time in proportion as SN 2002ap faded. Figure 1 shows the difference between their *BVRI* magnitudes after 2003 July, when the optical flux of star B became detectable. (It was not possible to make the same plot in the NIR because star A was usually outside or on the edge of the InSb detector.) The error bars estimated from photon statistics are in good agreement with the dispersion of the data points, so that it is not necessary to regard stars A and B as variable.

Simple aperture photometry was used throughout, and the aperture magnitude of SN 2002ap was obtained as the magnitude difference between SN 2002ap and star A or B. An aperture size of 6.″9 was adopted for all images, which minimizes the dispersion of the differential photometry. However, special care was taken for reliable magnitude determination of SN 2002ap, given the presence of a faint background object within a distance of about 1″. This object became distinguishable from SN 2002ap when SN 2002ap became sufficiently faint after solar conjunction in 2003. In 2003 December, SN 2002ap faded compared to the background object, and it was easy to resolve SN 2002ap and the object separately. Then, using the IRAF DAOPHOT package, the point-spread function (PSF) magnitude of the object was measured several times when the seeing was relatively good. This way, the PSF magnitude of the object was determined as $B = 21.7 \pm 0.5$, $V = 21.6 \pm 0.2$, $R = 21.25 \pm 0.12$, $I = 20.62 \pm 0.17$, $J = 20.0 \pm 0.1$, $H = 19.3 \pm 0.1$, and $K = 19.1 \pm 0.3$. These fluxes were subtracted from each aperture photometry of SN 2002ap.

Moreover, reference star B in NIR photometry has a faint nearby star which is about 4 mag fainter. Photometry was performed on the images where this faint nearby star was subtracted using IRAF DAOPHOT package.

2.2. *Observed Light Curves*

The *BVRIJHK* data taken over 42 nights from 2002 June 12 to 2003 August 29 are tabulated in Table 1. The uncertainty in

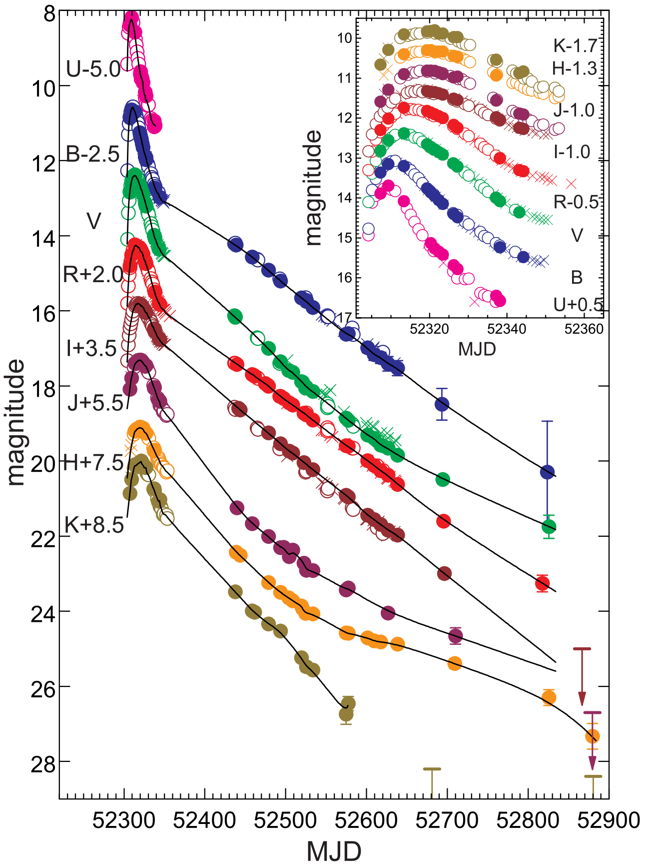

Fig. 2.—*UBVRIJHK* LCs of SN 2002ap for the first 1.5 yr after discovery obtained with the MAGNUM Telescope (*filled circles*). Also shown are the *UBVRI* data reported by Foley et al. (2003; *open circles*) and Pandey et al. (2003a, 2003b; *crosses*) and the early-time *JHK* data by Nishihara et al. (2002; *also open circles*). The LCs are shifted vertically in order to avoid overlap. Solid lines are *B*-spline fittings to the data, excluding the Pandey and Foley late-time ones.

each magnitude was derived combining in quadrature the magnitude dispersion from the frames obtained during the same night and the magnitude error of reference star A for *BVRI*, or B for *JHK*. A small error of 0.01 mag was added in quadrature for the *BVRI* magnitudes, taking into account the nonlinearity correction error between SN 2002ap and the reference star A. Another 0.01 mag error caused by the seeing effect, arising from the profile difference between SN 2002ap and the reference star A, was also added. The absolute calibration error and the subtracted flux uncertainty of the background object were taken into account when evaluating the total photometry error. No color-term correction was applied to the magnitudes of SN 2002ap in the nebular phase, because strong line emissions and large color difference with respect to the main-sequence star make this correction particularly difficult, as demonstrated by Menzies (1989).

We show the MAGNUM *UBVRIJHK* LCs in Figure 2 (*filled circles*), combining the late-time data in Table 1 and the early-time data of Paper I. For comparison, we also show the *UBVRI* photometry of Pandey et al. (2003a, 2003b) (<340 days; *crosses*), that of Foley et al. (2003) (<320 days; *open circles*), and the early-time *JHK* photometry of Nishihara et al. (2002) (<50 days; *open circles*). Obviously, our LCs have the largest time span. They are unique also in that both the early and late phase were well covered in NIR, the first time for any SN Ib/c. To guide the eye, we made *B*-spline fits (*solid lines*) to the data, excluding the Pandey and Foley late-time ones.

It is clear from the figure that the decline of the late-time LC slowed down after 2002 September in several bands. We derived the decline rates and the date when the decline rate changed in each band by χ^2-fitting the late-time MAGNUM data using a broken line (see Table 2). Before the change, which took place between about day 210 and day 250, the decline rate was similar in all bands, i.e., about 0.016–0.022 mag day^{-1}. The change is most profound in the NIR, as the *J* and *H* LCs flattened from 0.018 mag day^{-1} to 0.012 and 0.008 mag day^{-1}, respectively. It is small for most optical bands, although the *V* LC did flatten from 0.021 to 0.014 mag day^{-1}. As a result, the NIR contribution to the total flux increased significantly going to very late times. This is discussed further in the next section.

Most of our late-time data agree well with the Foley et al. (2003) ones, although their *B* magnitudes are 0.1–0.2 mag brighter than ours after day 280 and their *I* magnitudes 0.1–0.25 mag brighter after day 160. The Pandey et al. (2003b) late-time data are 0.1–0.15 mag brighter than ours in the *B* band, 0.2–0.4 mag brighter in the *V* band, and 0.1–0.2 mag fainter in the *I* band. Those differences can be partly explained by measurement uncertainties inherent to practical broadband photometry of SNe (e.g., see Hamuy et al. 1990), since these objects have time-evolving and line-dominated spectra of nonstellar nature. Our late-time *BVRI* LCs can differ from the those of Vinkó et al. (2004) and Doroshenko et al. (2003) by as much as 0.3 mag. However, their data were less well sampled than ours.

The late-time evolution of the optical colors, $B-V$, $V-R$, and $R-I$, is very different between SN 2002ap and SN 1998bw, as shown in Figure 3. In particular, $V-R$ of SN 2002ap between days 140 and 330 is about 0.3–0.6 mag larger and $B-V$ between days 200 and 340 about 0.3 mag smaller than in SN 1998bw. This can be easily understood within the context of spectroscopy. In the nebular phase, the spectra of both SNe were dominated by [O I] $\lambda\lambda6300$, 6364 in the *R* band, [Fe II] multiplets in the *V* and *B* bands, and Mg I] $\lambda4571$ in the *B* band, while Ca II] $\lambda\lambda7291$, 7324 may also contribute to the *R* and *I* photometry and the Ca II NIR triplet to the *I* photometry depending on the actual filter cutoff. As discussed by Foley et al. (2003), SN 2002ap has the strongest [O I] $\lambda\lambda6300$, 6364 and Mg I] $\lambda4571$ nebular emissions of any SN published. However, its [Fe II] multiplets are much weaker than in SN 1998bw, a consequence of much less ^{56}Ni ejected by SN 2002ap. Between days 390 and 520, $V-R$ and $R-I$ dropped and $B-V$ rose rapidly. This may indicate a flux shift from emissions of intermediate-mass elements to [Fe II] multiplets. Unfortunately, no observed spectra have so far been obtained for Type Ib/c SNe at such late times.

3. DISCUSSION

3.1. *Bolometric Light Curve*

We built the OIR bolometric LC integrating the *BVRIJHK* broadband flux (see Paper I for details). A reddening of $E(B-V)=0.09\pm0.01$ was corrected for (Takada-Hidai et al. 2002), and a distance modulus of 29.5 was adopted (but see Hendry et al. 2005).

The LC is shown in Figure 4, extending that in Paper I to ∼580 days since explosion. It consists of three independent data sets, which agree with one another. Most of the data (*filled circles*), tabulated in Table 3 (*late time*) and Paper I (*early time*), were made from the MAGNUM photometry. We interpolated and extrapolated the observations to estimate the *K* magnitudes between days 280 and 340 and the *J* and *I* magnitudes at day 520. For epochs <11 days, the observations of Mattila et al. (2002), Gal-Yam et al. (2002), and Cook et al. (2002) were used for

TABLE 2

Decline Rates of Light Curves of SN 2002ap in the Nebular Phase

	Band							
Parameter	*B*	*V*	*R*	*I*	*J*	*H*	*K*	Bolometric
Epoch range (MJD)	52438.6–52533.5	52437.6–52533.5	52439.6–52817.6	52441.6–52696.2	52439.6–52508.5	52438.6–52524.6	52437.6–52577.5	52438.5–52533.5
Decline rate (mag day^{-1})	0.017 ± 0.0004	0.021 ± 0.0002	0.016 ± 0.0001	0.017 ± 0.0001	0.018 ± 0.001	0.018 ± 0.001	0.022 ± 0.001	0.018 ± 0.0003
Epoch range (MJD)	52574.5–52823.6	52574.5–52825.6	. . .	. . .	52522.6–52710.2	52533.5–52879.5	. . .	52574.5–52879.5
Decline rate (mag day^{-1})	0.015 ± 0.002	0.014 ± 0.001	. . .	. . .	0.012 ± 0.001	0.008 ± 0.0005	. . .	0.014 ± 0.001
Date of change (MJD)	52545 ± 5	52535 ± 1	. . .	. . .	52514 ± 4	52532 ± 4	. . .	52558 ± 3

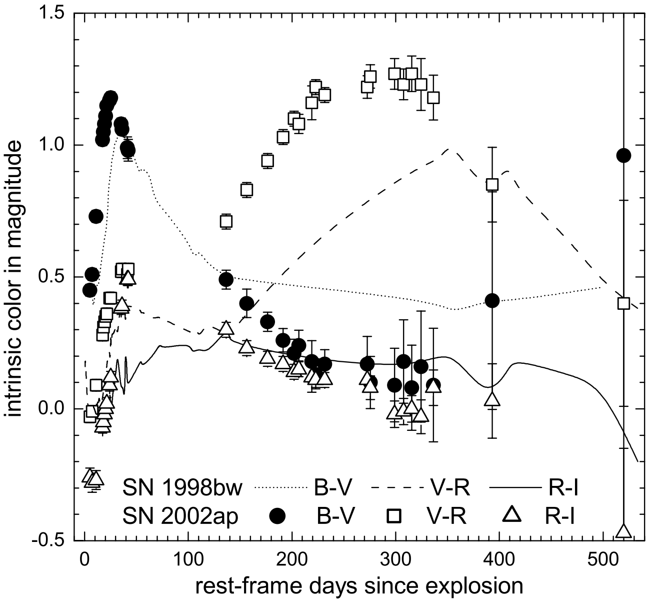

FIG. 3.—Evolution of optical colors, $B-V$, $V-R$, and $R-I$, of SN 2002ap compared with that of SN 1998bw. The colors of SN 2002ap are calculated from the MAGNUM photometry, corrected for $E(B-V)=0.09$, while those of SN 1998bw from the photometry in Galama et al. (1998), Patat et al. (2001), and Sollerman et al. (2002), corrected for $A(V)=0.1$.

interpolation. Bolometric magnitudes at day 407 and 578 (*triangles*) were converted from H magnitudes using approximate bolometric corrections. The other two data sets were based on the Foley et al. (2003) (*open circles*) and Pandey et al. (2003a, 2003b) (*crosses*) optical photometry, respectively, which was combined with the Nishihara et al. (2002) and our *JHK* photometry.

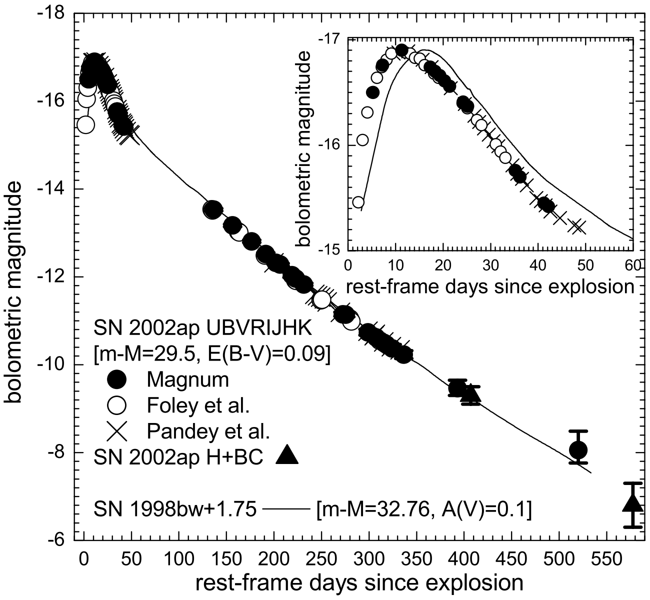

FIG. 4.—OIR bolometric LC of SN 2002ap constructed using the MAGNUM *UBVRIJHK* photometry, assuming $m-M=29.5$ and $E(B-V)=0.09\pm0.01$, compared with that of SN 1998bw [$z=0.0085$, $m-M=32.76$, and $A(V)=0.1\pm0.1$]. Also shown are bolometric magnitudes based on the Foley et al. (2003) and Pandey et al. (2003a, 2003b) optical photometry, which are combined with the MAGNUM and Nishihara et al. (2002) *JHK* photometry, and the ones estimated from the MAGNUM H photometry using approximate bolometric corrections. The SN 1998bw bolometric LC is shifted down by 1.75 mag to match the peak brightness of SN 2002ap. It is constructed using the photometry in Galama et al. (1998), Patat et al. (2001), and Sollerman et al. (2002).

TABLE 3

BOLOMETRIC MAGNITUDES OF SN 2002ap

MJD[a]	Day[b]	$M_{\rm bol}$	$L_{\rm NIR}/L_{\rm bol}$ (%)
52438.5	136.5	-13.53 ± 0.03	23
52458.5	156.5	-13.17 ± 0.03	22
52478.5	176.5	-12.81 ± 0.03	22
52493.5	191.5	-12.52 ± 0.03	22
52504.0	202.0	-12.32 ± 0.03	21
52508.5	206.5	-12.28 ± 0.03	23
52521.0	219.0	-12.04 ± 0.05	21
52525.0	223.0	-11.96 ± 0.03	21
52533.5	231.5	-11.83 ± 0.03	22
52574.5	272.5	-11.15 ± 0.05	23
52577.5	275.5	-11.14 ± 0.05	24
52601.0	299.0	-10.74 ± 0.07	25
52609.5	307.5	-10.62 ± 0.07	26
52617.5	315.5	-10.50 ± 0.07	26
52626.5	324.5	-10.37 ± 0.09	29
52638.5	336.5	-10.23 ± 0.09	29
52695.0	393.0	$-9.47^{+0.17}_{-0.18}$	39
52709.0	407.0	-9.3 ± 0.2	...
52822.0	520.0	$-8.06^{+0.30}_{-0.43}$	54
52879.5	577.5	-6.8 ± 0.5	...

[a] With an accuracy of 0.5 days due to data interpolation/extrapolation.
[b] With respect to the explosion date (MJD 52302.0).

The bolometric LC at late time has a shape similar to that of SN 1998bw (Fig. 4; *squares*), another hypernova, although the latter was much brighter. The SN 1998bw LC in Figure 4 is shifted down by 1.75 mag to match the peak magnitude of SN 2002ap. Both LCs show a similar late-time slowing-down. For SN 2002ap, the decline rate changed from ~0.018 mag day^{-1} between days 130 and 230 to ~0.014 mag day^{-1} between days 270 and 580. For SN 1998bw, the decline rate was ~0.019 mag day^{-1} between days 70 and 220 and ~0.014 mag day^{-1} between days 320 and 540. For comparison, the late-time bolometric LC of another hypernova, SN 1997ef, followed the decay rate of ^{56}Co, i.e., ~0.01 mag day^{-1} (Mazzali et al. 2004). On the other hand, SN 2002ap reached its light maximum ~5 days earlier than SN 1998bw did, although their peak widths are actually comparable (Fig. 4, *inset*).

3.2. *Spectral Energy Distribution*

We show the SED of SN 2002ap at five typical late epochs in Figure 5, where the monochromatic fluxes converted from the MAGNUM *BVRIJHK* photometry are connected using spline-fitting curves. The observed upper limits of the K-band flux at day 393 and 520 are marked by arrows. Zero flux was assumed at both the blue edge of the B band and the red edge of the K band. We used such SEDs to obtain the OIR bolometric magnitudes.

The SEDs are dominated by the flux in the R and I bands before about day 340–390, which was mainly due to strong [O I], Ca II], and Ca II emissions (Foley et al. 2003). The B-bump at the three intermediate epochs reflects the contribution of Mg I] λ4571. After about day 340–390, the V flux, attributed to [Fe II] multiplets, increased relative to that in other optical bands, while the I-band-dominated Ca II emissions died away.

The NIR flux contribution rose rapidly after ~day 300 (Fig. 6). This can been seen in Figure 5 as a big H bump in the SED and also in Figure 2 as a significant flattening of the H and J LCs. To explain this, we examined the synthesized NIR spectra of the models that reproduce the late-time optical spectra of SN 2002ap

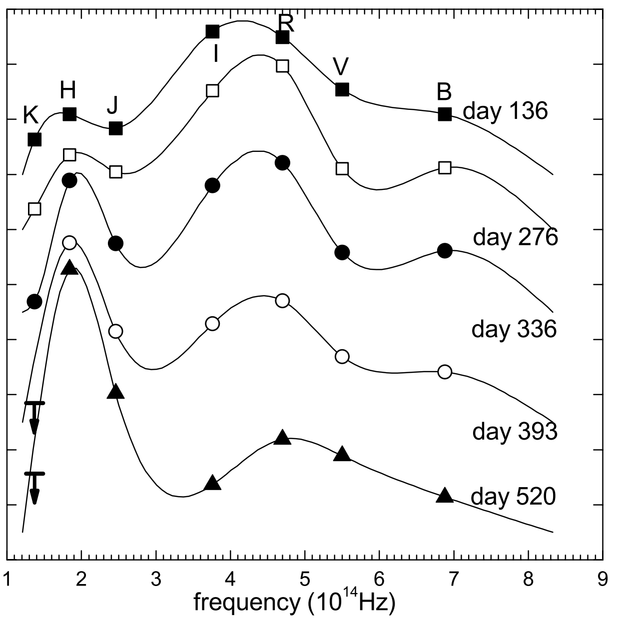

FIG. 5.—SEDs of SN 2002ap at five typical late epochs, constructed using the MAGNUM photometry. The *BVRIJHK* monochromatic flux is connected using spline-fitting curves. Capped arrows represent flux upper limits in the *K* band.

(P. A. Mazzali et al. 2006, in preparation). The most likely candidates are the strong [Si I] 1.646 and 1.608 μm lines, while the 1.099 μm line may account for the concurrent *J*-band flux increase. The lines were already developed in the day ~200 NIR spectrum of Gerardy et al. (2004), although they were still not as strong as a 1.5 μm feature, possibly Mg I emission. We note in passing that the appearance of the CO first-overtone band in that spectrum suggested by those authors seems to coincide with the *K*-band LC steepening seen in Figure 2.

The late-time *H*-band spectra of SN 1983N, taken by Graham et al. (1986) and of very low resolution, showed a strong 1.65 μm feature, which was explained by those authors as [Fe II] lines but was soon, together with an adjacent feature, reidentified as [Si I] lines by Oliva (1987). These [Si I] NIR features can also be found in the synthetic late-time spectra of Type Ib SNe computed by Fransson & Chevalier (1989).

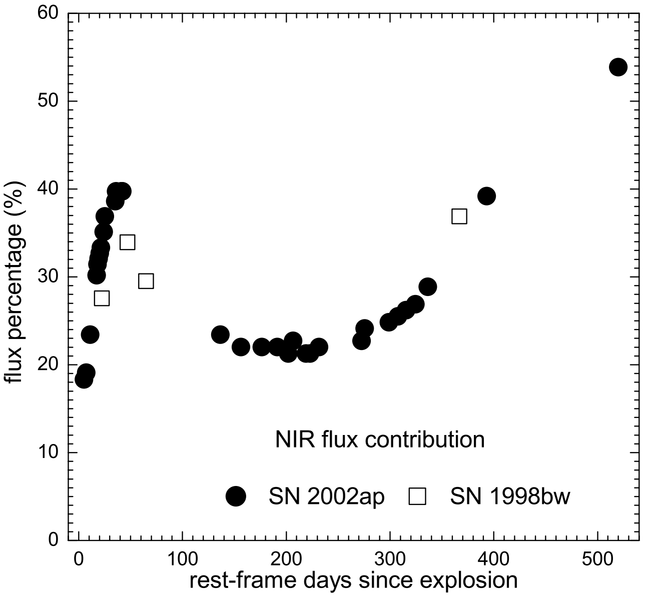

FIG. 6.—Contribution of NIR flux to the total OIR bolometric flux in SN 2002ap compared with that in SN 1998bw.

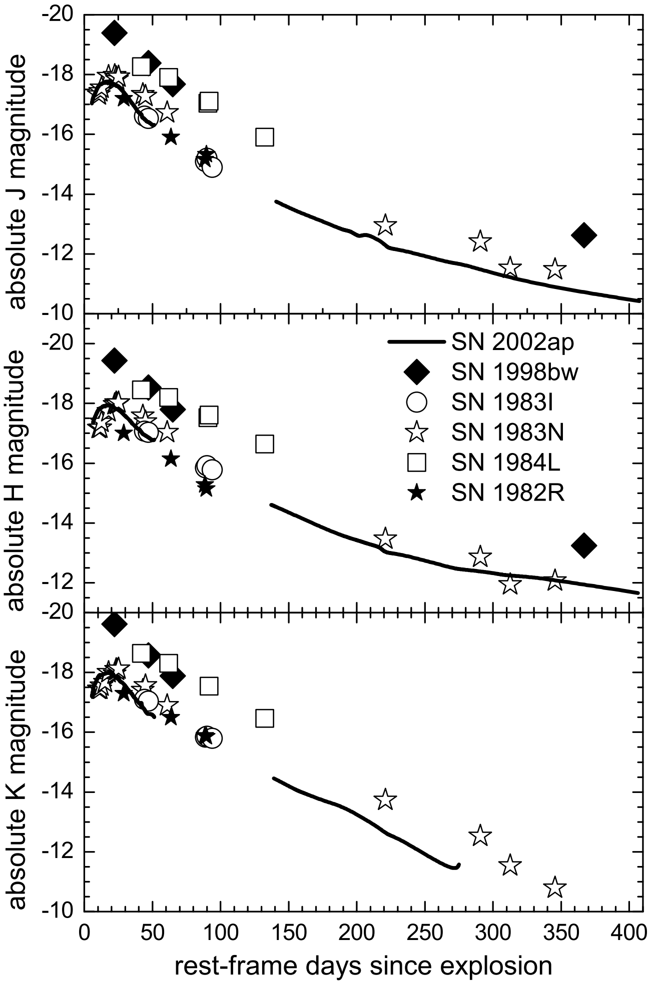

FIG. 7.—Absolute *J* (*top*), *H* (*middle*), and *K* (*bottom*) LCs of the Type Ib/c SNe whose late-time NIR photometry are available. See Table 4 for data references and adopted SN parameters.

3.3. *Late-Time NIR Light Curves of Type Ib/c Supernovae*

In Figure 7 we compare the late-time *JHK* LCs of SN 2002ap with those of other Type Ib/c SNe (see Table 4). SN 1998bw and SN 1984L were 1.5–2.5 mag brighter than all other SNe, indicating a large mass of ^{56}Ni ejected. The NIR LCs of SN 1984L were relatively slow, as was its late-time optical LC which was modeled using very massive ejecta but with normal kinetic energy (Swartz & Wheeler 1991; Baron et al. 1993). The few points of SN 1998bw, when shifted down by 1.8 mag (*J*), 1.5 mag (*H*), and 1.7 mag (*K*), respectively, fall on the LCs of SN 2002ap. The LCs of SN 1983N have later and broader peaks than those of SN 2002ap, but they become similar between the *J*-band and *H*-band day ~200 and 350. On the other hand, the *JHK* data of SN 1983I and 1982R seem to bridge the LC gap in SN 2002ap data between day 50 and day 140 (solar conjunction).

Figure 7 contradicts the picture that SNe 1983I, 1983N, and 1984L have similar *JHK* LCs (Elias et al. 1985). Type Ib/c SNe were first established as a new class by those authors, who showed that these SNe have similar *JHK* LCs, which are different from those of Type Ia SNe (and also by Wheeler & Levreault [1985] through an analysis of the optical spectra). They artificially shifted the data of SN 1983I and SN 1984L in both phase and brightness in order to match the NIR LCs of SN 1983N.

TABLE 4

Type Ib/c Supernovae with Late-Time NIR Photometry

Parameter	SN 1982R	SN 1983I	SN 1983N	SN 1984L	SN 1998bw
Spectroscopic type	Ib/c	Ic	Ib	Ib	Ic, hypernova
Distance modulus[a]	31.2	31.0	28.25	31.5	32.76
Extinction A_V[b]	0.5	0.04	0.2	0.09	0.1 ± 0.1
Explosion date (UT)[c]	1982 Sep 28	1983 Apr 25	1983 Jul 1	1984 Aug 5	1998 Apr 25.9
JHK photometric data sources	Mattila & Meikle (2001)	Elias et al. (1985)	Elias et al. (1985), Mattila & Meikle (2001)	Elias et al. (1985)	Patat et al. (2001), Sollerman et al. (2002)

[a] Using $h_0 = 0.72$, $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$; 1982R and 1984L, radial velocity corrected for LG infall onto Virgo (LEDA; Paturel et al. 1997); 1983I, see § 3.4; 1983N, Cepheids (Thim et al. 2003); 1998bw, $z = 0.0085$ (Galama et al. 1998).

[b] 1982R, Clocchiatti et al. (1996); 1983I, 1983N, and 1984L, Galactic Schlegel et al. (1998); 1998bw, Patat et al. (2001).

[c] 1982R, 26 days before discovery (Porter & Filippenko 1987); 1983I, see § 3.4; 1983N, 2 days before discovery and 16 days before B maximum (Porter & Filippenko 1987); 1984L, 15 days before light maximum and by comparison with SN 1985F (Tsvetkov 1987; Schlegel & Kirshner 1989); 1998bw, GRB 980425 (Galama et al. 1998).

Their SN 1983I data were assigned epochs 20 days later than ours, and SN 1984L 14 days earlier. Our epoch estimates are more reasonable because we based them on optical LCs and spectra that are better observed and understood than the NIR data.

3.4. *Was SN 1983I Similar to SN 2002ap?*

Inspecting by eye the only published spectrum of SN 1983I (Wheeler et al. 1987), we noticed that it resembles those of SN 2002ap between 2002 February 16 and 22 (Kinugasa et al. 2002). The similarity can be seen not only in the overall shape and strongest line features, but also in relatively weak ones, like those near 4900, 5900, and 6200 Å. The spectrum was taken on 1983 May 17, 5 days after discovery. We estimate the epoch of that spectrum as 22 ± 3 days since explosion, through this comparison, and hence derive an explosion date of 1983 April 25.

The LCs of SN 1983I seem to match those of SN 2002ap not only in the NIR (Fig. 7) but also in the optical (Fig. 8), if our estimates of the explosion date and the distance modulus are correct. We adopt 31.0 as the distance modulus to the host galaxy of SN 1983I, NGC 4051 in the Ursa Major cluster (Tsvetkov 1985). This value is also close to the average of the distance modulus of the Ursa Major cluster (31.4; Tully & Pierce 2000), and that corresponding to its radial velocity corrected for the Local Group infall onto Virgo (30.5; LEDA[11]; Paturel et al. 1997).

Therefore, SN 1983I could be a precedent of the unusual SN 2002ap, which lies at the low-mass low-energy end of hypernovae (Mazzali et al. 2002). However, its data are insufficient for us to make a solid conclusion.

3.5. *Modeling the Late-Time Light Curve*

The late-time bolometric LC of SN 2002ap declines more slowly than that of the one-dimensional model of Mazzali et al. (2002) that best reproduced the early-time spectra and LC (see Fig. 9, *dotted line*). This is expected, since the LC follows that of SN 1998bw closely in terms of the decline rate, as shown in Figure 4. The best-fitting one-dimensional model for the early-time spectra and LC of SN 1998bw also fails to explain its late-time spectrum and LC (Nakamura et al. 2001; Mazzali et al. 2001). To mimic the outcome of two-dimensional jet-induced explosion calculations (Maeda et al. 2002), which applies to SN 1998bw and

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[11] See http://leda.univ-lyon1.fr.

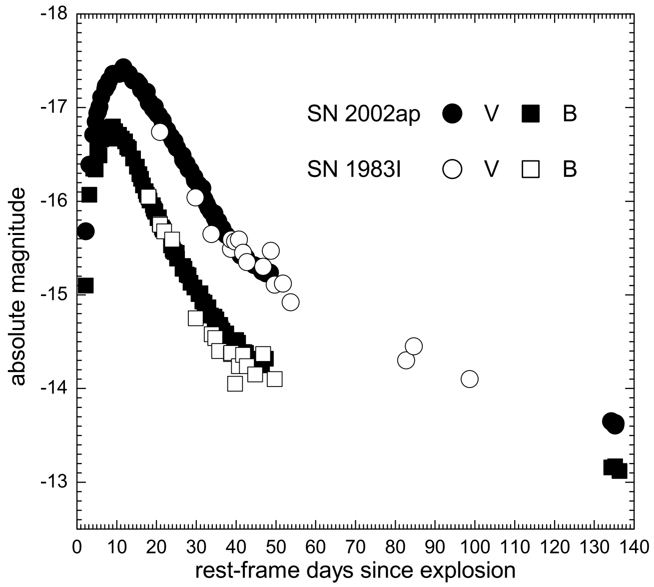

Fig. 8.—Absolute *B* and *V* LCs of the Type Ic SN 1983I (Tsvetkov 1985), assuming $m - M \approx 31.0$ and an explosion date of 1983 April 25 (see Table 4), compared with those of SN 2002ap.

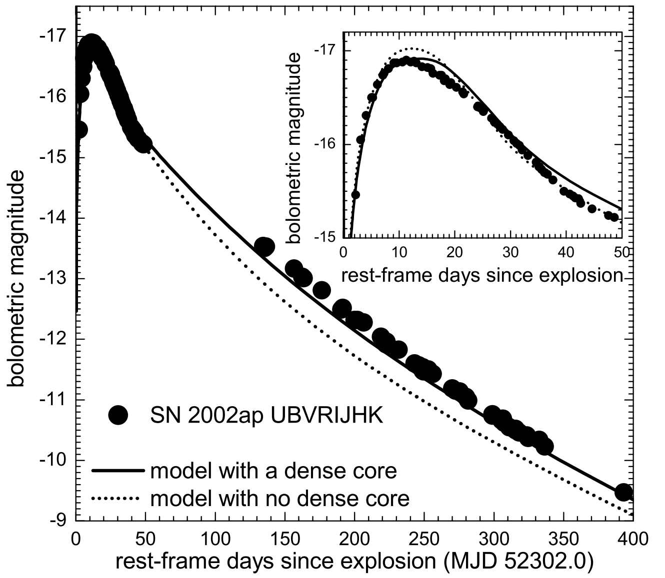

Fig. 9.—OIR bolometric LC of SN 2002ap compared with the best-fitting LCs of the one-dimensional ejecta model with a dense core at $v < 3000$ km s^{-1} (total $M_{\rm ej} \approx 3\ M_\odot$), and that without a dense core (total $M_{\rm ej} \approx 2.5\ M_\odot$). Both models have total kinetic energy of 4×10^{51} ergs and 0.08 $M_\odot$ ^{56}Ni.

may also apply to SN 2002ap, Maeda et al. (2003) introduced a dense core. That core absorbs γ-rays efficiently at late time. Using this structure, the slow LC decline of hypernovae was reproduced by those authors using a Monte Carlo radiative transfer code, but with simplified physics.

We tested the dense-core scenario on SN 2002ap using our sophisticated one-dimensional SN radiation hydrodynamic and γ-ray transfer code (Iwamoto et al. 2000; Mazzali et al. 2002; Deng et al. 2005). The best-fitting model (Fig. 9, *solid line*) has $\sim$0.6 $M_\odot$ ejecta below 3000 km s^{-1}, compared with 0.1 $M_\odot$ in the model without a dense core, and $\sim$0.01 $M_\odot$ low-velocity ^{56}Ni. Compared with Mazzali et al. (2002), who modeled only the early-time observations, the total ejecta mass has increased from 2.5 to 3 $M_\odot$, but with little change in the total ^{56}Ni mass (0.08 $M_\odot$) and the kinetic energy (4×10^{51} ergs). A dense ejecta core is also required in one-dimensional late-time spectrum models (P. A. Mazzali et al. 2006, in preparation) in order to explain the observed sharp line cores of [O I] and Mg I] (Leonard et al. 2002; Foley et al. 2003).

A dense core cannot be formed in one-dimensional explosion simulations for hypernovae (Nakamura et al. 2001), but it is a natural product of two-dimensional jet-induced explosions (Maeda et al. 2002). This strongly indicates asymmetry in the SN 2002ap explosion, an intrinsic feature also shared by other hypernovae. Evidence of asymmetry in SN 2002ap can also be found in spectropolarimetry (Kawabata et al. 2002; Leonard et al. 2002; Wang et al. 2003), which shows an intrinsic continuum polarization varying around 0.5%, corresponding to an asphericity of $\sim$10% for the bulk of the ejecta.

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REFERENCES

Baron, E., Young, T. R., & Branch, D. 1993, ApJ, 409, 417
Berger, E., Kulkarni, S. R., & Chevalier, R. A. 2002, ApJ, 577, L5
Björnsson, C.-I., & Fransson, C. 2004, ApJ, 605, 823
Clocchiatti, A., Wheeler, J. C., Benett, S., & Frueh, M. 1996, ApJ, 459, 547
Cook, L. M., Katkova, E. V., Sokolov, N. A., & Guseva, I. S. 2002, Inf. Bull. Variable Stars, 5283, 1
Danziger, J., Della Valle, M., Palazzi, E., & Pian, E. 2002, IAU Circ., 7838, 2
Deng, J., Tominaga, N., Mazzali, P., Maeda, K., & Nomoto, K. 2005, ApJ, 624, 898
Doroshenko, V. T., Sergeev, S. G., Merkulova, N. I., & Sergeeva, E. A. 2003, Astrophysics, 46, 365
Elias, J. H., Matthews, K., Neugebauer, G., & Persson, S. E. 1985, ApJ, 296, 379
Foley, R. J., et al. 2003, PASP, 115, 1220
Fransson, C., & Chevalier, R. A. 1989, ApJ, 343, 323
Galama, T. J., et al. 1998, Nature, 395, 670
Gal-Yam, A., Ofek, E. O., & Shemmer, O. 2002, MNRAS, 332, L73
Gerardy, C. L., Fesen, R. A., Marion, G. H., Höflich, P., Wheeler, J. C., Nomoto, K., & Motohara, K. 2004, in Cosmic Explosions in Three Dimensions, ed. P. Höflich, P. Kumer, & J. C. Wheeler (Cambridge: Cambridge Univ. Press), 57
Graham, J. R., Meikle, W. P. S., Allen, D. A., Longmore, A. J., & Williams, P. M. 1986, MNRAS, 218, 93
Hamuy, M., Suntzeff, N. B., Bravo, J., & Phillips, M. M. 1990, PASP, 102, 888
Hendry, M. A., et al. 2005, MNRAS, 359, 906
Hunt, L. K., et al. 1998, AJ, 115, 2594
Hurley, K., et al. 2002, GCN. Circ. 1252, http://gcn.gsfc.nasa.gov/gcn/gcn3/1252.gcn3
Iwamoto, K., et al. 1998, Nature, 395, 672
———. 2000, ApJ, 534, 660
Kawabata, K. S., et al. 2002, ApJ, 580, L39
Kinugasa, K., et al. 2002, ApJ, 577, L97
Kobayashi, Y., Yoshii, Y., Peterson, B. A., Minezaki, T., Enya, K., Suganuma, M., & Yamamuro, T. 1998a, Proc. SPIE, 3354, 769
Kobayashi, Y., et al. 1998b, Proc. SPIE, 3352, 120
Leonard, D. C., Filippenko, A. V., Chornock, R., & Foley, R. J. 2002, PASP, 114, 1333
Maeda, K., Mazzali, P. A., Deng, J., Nomoto, K., & Yoshii, Y. 2003, ApJ, 593, 931
Maeda, K., Nakamura, T., Nomoto, K., Mazzali, P. A., Patat, F., & Hachisu, I. 2002, ApJ, 565, 405
Malesani, D, et al. 2004, ApJ, 609, L5
Mattila, S., & Meikle, W. P. S. 2001, MNRAS, 324, 325
Mattila, S., Meikle, P., & Chambers, K. 2002, IAU Circ., 7820, 1
Mazzali, P. A., Deng, J, Maeda, K., Nomoto, K., Filippenko, A. V., & Matheson, T. 2004, ApJ, 614, 858
Mazzali, P. A., Nomoto, K., Patat, F., & Maeda, K. 2001, ApJ, 559, 1047
Mazzali, P. A., et al. 2002, ApJ, 572, L61
———. 2003, ApJ, 599, L95
Menzies, J. W. 1989, MNRAS, 237, 21
Nakamura, T., Mazzali, P. A., Nomoto, K., & Iwamoto, K. 2001, ApJ, 550, 991
Nakano, S., Kushida, R., Kushida, Y., & Li, W. 2002, IAU Circ., 7810, 1
Nishihara, E., Kinugasa, K., Hashimoto, O., Okuda, H., & Yamaoka, H. 2002, in Proc. of the IAU 8th Asian-Pacific Regional Meeting, Vol. II, ed. S. Ikeuchi, J. Hearnshaw, & T. Hanawa (Tokyo: ASJ), 347
Nomoto, K., Maeda, K., Mazzali, P. A., Umeda, H., Deng, J., & Iwamoto, K. 2004, in Stellar Collapse, ed. C. L. Fryer (Dordrecht: Kluwer), 277
Oliva, E. 1987, ApJ, 321, L45
Pandey, S. B., Anupama, G. C., Sagar, R., Bhattacharya, D., Sahu, D. K., & Pandey, J. C. 2003a, MNRAS, 340, 375
Pandey, S. B., Sahu, D. K., Anupama, G. C., Bhattacharya, D., & Sagar, R. 2003b, Bull. Astron. Soc. India, 33, 351
Patat, F., et al. 2001, ApJ, 555, 900
Paturel, G., et al. 1997, A&AS, 124, 109
Porter, A. C., & Filippenko, A. V. 1987, AJ, 93, 1372
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schlegel, E. M., & Kirshner, R. P. 1989, AJ, 98, 577
Sharina, M. E., Karachentsev, I. D., & Tikhonov, N. A. 1996, A&AS, 119, 499
Smartt, S. J., Vreeswijk, P. M., Ramirez-Ruiz, E., Gilmore, G. F., Meikle, W. P. S., Ferguson, A. M., & Knapen, J. H. 2002, ApJ, 572, L147
Soderberg, A., M., Nakar, E., & Kulkarni, S. R. 2006, ApJ, 638, 930
Sohn, Y.-J., & Dvidge, T. J. 1996, AJ, 111, 2280
Sollerman, J, et al. 2002, A&A, 386, 944
Soria, R., & Kong, A. K. H. 2002, ApJ, 572, L33
Soria, R., Pian, E., & Mazzali, P. A. 2004, A&A, 413, 107
Stanek, K. Z., et al. 2003, ApJ, 59, 17
Sutaria, F. K., Chandra, P., Bhatnagar, S., & Ray, A. 2003, A&A, 397, 1011
Swartz, D. A., & Wheeler, J. C. 1991, ApJ, 379, L13
Takada-Hidai, M., Aoki, W., & Zhao, G. 2002, PASJ, 54, 899
Thim, F., Tammann, G. A., Saha, A., Dolphin, A., Sandage, A., Tolstoy, E., & Labhardt, L. 2003, ApJ, 590, 256
Tominaga, N., Deng, J., Mazzali, P. A., Maeda, K., Nomoto, K., Pian, E., Hjorth, J., & Fynbo, J. P. U. 2004, ApJ, 612, L105
Totani, T. 2003, ApJ, 598, 1151
Tsvetkov, D. Y. 1985, Soviet Astron., 29, 211
———. 1987, Soviet Astron. Lett., 13, 376
Tully, R. B., & Pierce, M. J. 2000, ApJ, 533, 744
Vinkó, J., et al. 2004, A&A, 427, 453
Wang, L., Baade, D., Höflich, P., & Wheeler, J. C. 2003, ApJ, 592, 457
Wheeler, J. C., Harkness, R. P., Barker, E. S., Cochran, A. L., & Wills, D. 1987, ApJ, 313, L69
Wheeler, J. C., & Levreault, R. 1985, ApJ, 294, L17
Yoshii, Y. 2002, in New Trends in Theoretical and Observational Cosmology, ed. K. Sato & T. Shiromizu (Tokyo: Univ. Acad. Press), 235
Yoshii, Y., et al. 2003, ApJ, 592, 467 (Paper I)