

THE OPTICAL/NEAR-INFRARED LIGHT CURVES OF SN 2002ap FOR THE FIRST 140 DAYS AFTER DISCOVERY

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ABSTRACT

Supernova (SN) 2002ap in M74 was observed in the *UBVRJHK* bands for the first 40 days following its discovery (2002 January 29) until it disappeared as a result of solar conjunction and then in June after it reappeared. The magnitudes and dates of peak brightness in each band were determined. While the rate of increase of the brightness before the peak is almost independent of wavelength, the subsequent rate of decrease becomes smaller with wavelength from the *U* to the *R* bands and is constant at wavelengths beyond the *I* band. The photometric evolution is faster than in the well-known “hypernovae” SNe 1998bw and 1997ef, indicating that SN 2002ap ejected less mass. The bolometric light curve of SN 2002ap for the full period of observations was constructed. The absolute magnitude is found to be much fainter than that of SN 1998bw but is similar to that of SN 1997ef, which lies at the faint end of the hypernova population. The bolometric light curve at the early epochs was best reproduced with the explosion of a C + O star that ejects $2.5 M_{\odot}$ with kinetic energy $E_K = 4 \times 10^{51}$ ergs. A comparison of the predicted brightness of SN 2002ap with that observed after solar conjunction may imply that γ -ray deposition at the later epochs was more efficient than in the model. This may be due to an asymmetric explosion.

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

1. INTRODUCTION

The discovery of hypernovae, i.e., supernovae (SNe) with explosion energies exceeding that of normal SNe and possibly linked with gamma-ray bursts, has motivated the creation of a close network between transient-object hunters, follow-up observers, and model builders. This network successfully functioned for the recent energetic Type Ic SN 2002ap, which appeared in the outer part of the nearby spiral galaxy M74 ($m - M = 29.5^{+0.1}_{-0.2}$, $D \approx 7.9$ Mpc; Sharina, Karachentsev, & Tikhonov 1996; Sohn & Davidge 1996). After its discovery on January 29 by Y. Hirose and confirmation the following day (Nakano et al. 2002), intensive worldwide follow-up observational programs (e.g., Gal-Yam, Ofek, & Shemmer 2002) were started, accumulating photometric and spectroscopic data. Theoretical models (e.g., Mazzali et al. 2002) have been used to constrain the physical properties of SN 2002ap.

Having received notification of the rare opportunity of a nearby SN event soon after its discovery, multiwavelength monitoring of the brightness of SN 2002ap in the *UBVRJHK* bands began with the multicolor imaging photometer (MIP) mounted on the MAGNUM 2 m telescope (Yoshii et al. 2002), which is located at a height of 3055 m at

the summit of Haleakala, on the island of Maui, Hawaii. The MAGNUM (Multicolor Active Galactic Nuclei Monitoring) Project was designed to monitor many active galactic nuclei (AGNs) at wavelengths from the UV/optical to the near-infrared (NIR) and to determine a redshift-independent distance to the AGNs from which the cosmological parameters could finally be determined (Yoshii 2002).

In this paper, the full set of *UBVRJHK* imaging observations of SN 2002ap taken during the first 40 days following its discovery until it disappeared as a result of solar conjunction and then in June after it reappeared is presented, including the first NIR light curves.⁷ These light curves are analyzed and compared with those of the hypernovae SNe 1998bw and 1997ef. The bolometric light curve, constructed for dates up to March 11 and then combined with one point in June, is compared with that synthesized using theoretical models.

2. IMAGING PHOTOMETRY

2.1. Observations

The MAGNUM telescope has a 2 m primary mirror and Ritchey-Chrétien optics giving a field of view of $33'$ (Kobayashi et al. 1998b). The MIP camera, installed at the focal point of the bent Cassegrain focus, contains an SiTe CCD (1024×1024 pixels, $0''.277$ pixel⁻¹) and an SBRC InSb array (256×256 pixels, $0''.346$ pixel⁻¹). A dichroic beam splitter enables simultaneous imaging through optical (*UBVRI*) and NIR (*ZJHK'KL'*) filters (Kobayashi et al. 1998a). The effective area of each frame over which the light

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⁷ A part of the data presented here was previously used in Mazzali et al. (2002) for the sake of theoretical modeling.

was received by the detector is $119'' \times 119''$ for the CCD and $88''5 \times 88''5$ for the InSb. Observations of SN 2002ap are on the Johnson-Cousins system after correction for color terms and color offsets. SN 2002ap ($\alpha = 01^{\text{h}}36^{\text{m}}23^{\text{s}}.85$, $\delta = +15^{\circ}45'13''.2$ [J2000.0], Nakano et al. 2002) was observed in the *UBVRIJHK* bands from 2002 February 2 to March 11 before solar conjunction. Observations performed during 2002 June, the first month after solar conjunction, are also reported. Given the inferred explosion date, January 28 (Mazzali et al. 2002), our observation began only 5 days after the explosion. A nearby star ($\alpha = 01^{\text{h}}36^{\text{m}}19^{\text{s}}.49$, $\delta = +15^{\circ}45'20''.8$ [J2000.0]), known to be a double star, was of comparable brightness to SN 2002ap in the same CCD frame, so it was observed as a reference star for *UBVRI*.

Although SN 2002ap was visible only at low elevations (40° – 20°), either after sunset (for the observations before solar conjunction) or before sunrise (for the observations after solar conjunction), MIP's efficient splitting of the incident light allowed the successful completion of simultaneous multicolor imaging within an hour or so. Because of such simultaneous imaging, telescope dithering required primarily for *JHK* was also performed for *UBVRI* using three $10''$ steps. A typical exposure time for one step was 120 s for *U*, 40 s for each of *BVRI*, and 10 s for each of *JHK*. However, for the observations in June, the exposure time was prolonged within the saturation limits of the reference star. Typical seeing sizes of the stellar images were $1''.0$ – $1''.7$ in *V* and $0''.85$ – $1''.3$ in *K*.

Our observational strategy was to observe SN 2002ap, the infrared standard stars for *JHK* (Hunt et al. 1997), and the optical standard stars for *UBVRI* (Landolt 1992), irrespective of whether the night was photometric. Those observations were performed by interrupting the scheduled queue of our original program of observing AGNs. At the end of each night, dome-flat images for *BVRIJHK* and infrared dark images were obtained. However, twilight-flat images for *U* were obtained on other days.

2.2. Image Reduction

Image reduction was performed using our package of IRAF-based automated reduction software (MAGRED), which was developed for the MAGNUM Project. A simple pattern of noises, which was overlaid on the images by interference from the radio broadcast station near the telescope site, was removed from the bias region of each CCD frame. Then, for the CCD data reduction, nonlinear corrections, bias subtraction, flat-fielding based on the dome flat (twilight flat for *U*), and interpolation among bad pixels were applied to each frame in a standard manner. Sky subtraction was not employed because the difference between sky flat and dome flat was negligibly small except near the edge of each frame.

For the InSb data reduction, the noise pattern was removed from the image region of each frame, because the bias region is absent in the InSb. Then, similar corrections as above were made, but sky subtraction was done by using the sky flat taken at a time close to the observation of SN 2002ap. Flat images for *H* and *K* were generated as the difference between the dome-flat images taken with the light on and off, after correcting for illumination by comparing them with the sky flat. Flat images for *J* were taken similarly except that dark images were used instead of dome-flat images taken with the light off.

Multiperture photometry was used throughout, since SN 2002ap is located far from the center of M74, in a region where the sky background is sufficiently flat. An aperture size of $11''$ was chosen as a compromise between smaller apertures that reliably increase the S/N ratio and larger apertures that ensure constant and stable measured magnitudes of the reference double star. However, in order to enhance the S/N ratio, a smaller aperture was adopted for the *U*-band images taken on March 4–5 ($8''.3$) and for the images taken in June ($5''.5$ for *BVRI* and $8''.3$ for *JHK*).

Three CCD frames of SN 2002ap were obtained each night while dithering the telescope position, and aperture photometry was performed for each frame. The adopted aperture magnitude of SN 2002ap is the median of the three. However, for the *U*-band frames taken after February 21, the three frames were stacked before aperture photometry was performed. Figure 1 shows a series of color-coded images taken on eight different nights (February 2, 4, 8, 14, 16, 18, 22, and March 5), which give a visual impression of the optical color evolution of SN 2002ap.

Since each CCD frame is wide enough to cover both SN 2002ap and the reference star, the aperture magnitude of SN 2002ap was obtained via differential photometry between SN 2002ap and the reference star in the same CCD frame (Enya et al. 2002).

The magnitude calibration of the reference star in the CCD frame was carried out only on photometric nights, i.e., when the dispersion in instrumental magnitudes of SN2002ap and that for the reference star were comparable to the S/N ratio and also when it was judged to be a fine day from the MAGNUM cloud monitor data (M. Suganuma et al., in preparation) and by eye inspection of the weather. Whenever optical standard stars were observed more than twice at different elevations on a photometric night, the air-mass dependence and the magnitude zero points in each band were obtained so that the aperture magnitudes of the reference star were calibrated. Their respective medians and number of calibrations are $U(4) = 14.13 \pm 0.04$, $B(5) = 13.83 \pm 0.02$, $V(5) = 13.07 \pm 0.01$, $R(5) = 12.61 \pm 0.015$, and $I(3) = 12.15 \pm 0.01$, where the error is estimated as half of the difference between the brightest and faintest magnitudes for multiple calibrations in each band.

On the other hand, the InSb frame of the *JHK* observations is not wide enough to include any reference star of brightness comparable to SN 2002ap. Therefore, the aperture *JHK* magnitudes of SN 2002ap in individual image frames were calibrated using standards-based photometry, and for each band the median was adopted as the aperture magnitude of SN2002ap.

2.3. Observed Light Curves

Figure 2 shows the *UBVRIJHK* light curves based on the data taken on 14 nights during the period 2002 February 2–March 11, until SN 2002ap disappeared behind the Sun. These data are listed in Table 1, together with the data for five nights in June after solar conjunction. For the purpose of comparison, data reported by other authors are also shown in Figure 2.⁸

The magnitude error in each optical band is estimated as $\sigma_e^2 = \sigma_{\text{sn}}^2 + \sigma_{\text{ref}}^2 + \sigma_{*}^2$, where σ_{sn} and σ_{ref} are the photometric

⁸ Additional information on Szokoly (2002) is available at <http://www.aip.de/~gszokoly/sn2002ap/NOTES.sn2002ap>.

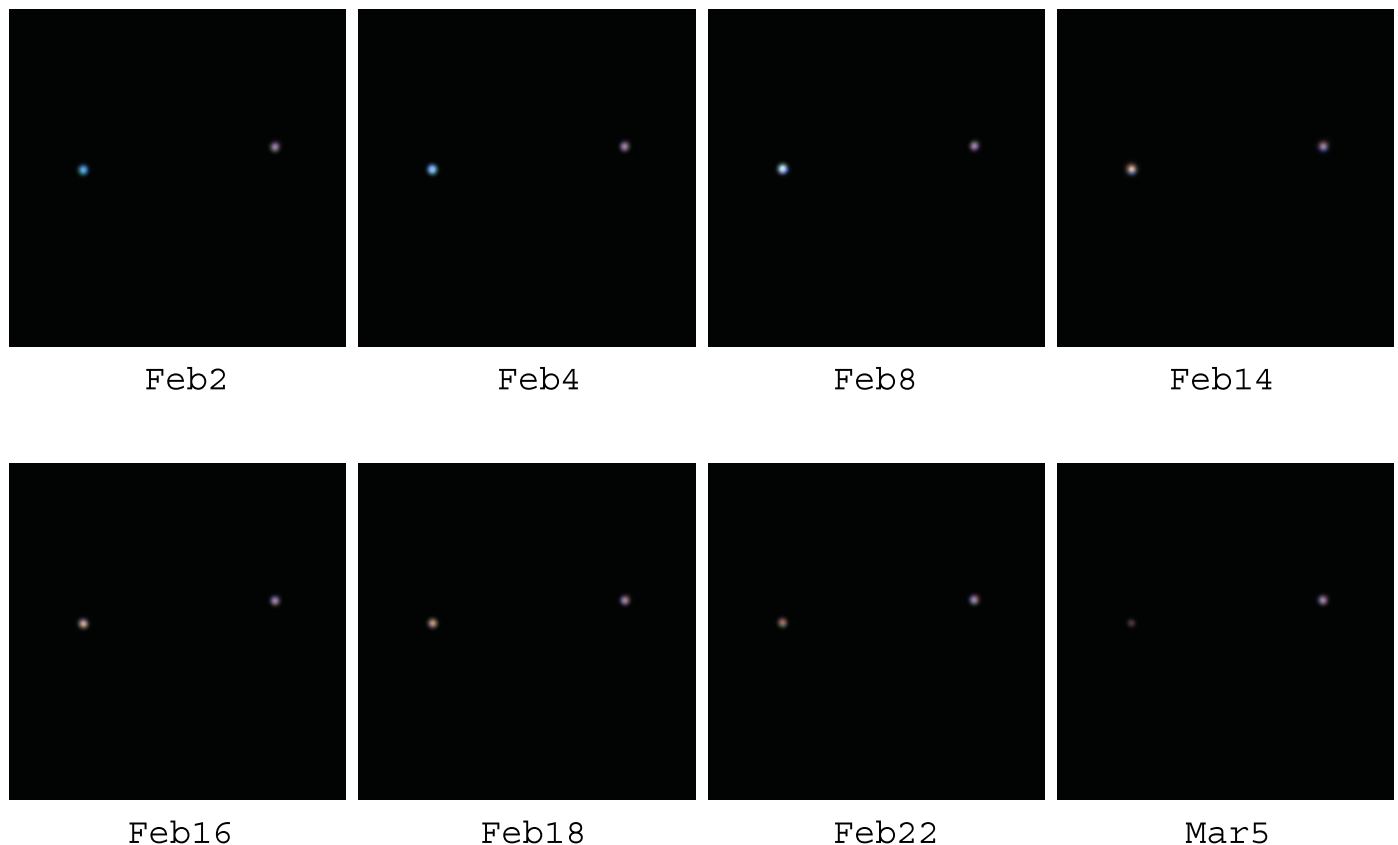


FIG. 1.—Series of optical color-coded images taken on different nights before and after the epoch of peak brightness of SN 2002ap, which is around February 8 for the V band. Each image with view size of $105'' \times 105''$ is made from the images of three B , V , and R filters. While the reference star with the red color on the right stays constant in color and brightness, SN 2002ap with the blue color on the left becomes brighter until February 8, thereafter becoming redder and fainter.

errors of SN 2002ap and the reference star, respectively, which were estimated from the output of IRAF PHOT, and σ_* is the magnitude calibration error of the reference star given in § 2.2. For June data taken when SN 2002ap faded, the use of a small aperture for both SN 2002ap and the reference double star introduced some small error because of their different brightness profiles. This error was estimated to be 0.01 mag and was incorporated in the quadrature.

The magnitude error in each NIR band is estimated as $\sigma_e^2 = \sigma_{\text{sn}}^2 + \sigma_{\text{std}}^2 + \sigma_{\text{zp}}^2$, where σ_{sn} and σ_{std} are the photometric errors of SN 2002ap and the standard stars, respectively, and σ_{zp} is the zero-point uncertainty of the standard stars caused by time-variant atmospheric conditions. The error σ_{sn} is basically given by the IRAF magnitude dispersion of SN 2002ap divided by the square root of the number of frames obtained during the same night. However, since the error given this way is smaller than the standard deviation of the instrumental magnitudes of SN 2002ap, additional errors likely arising from the flat fielding and the reduction procedure must also be added in quadrature. We adopted $\sigma_{\text{std}} = 0.01$ mag because all standard stars were observed with enough S/N. We adopted $\sigma_{\text{zp}} = 0.02$ mag for clear nights and 0.05 mag for poor conditions. The errors were larger when thin patchy clouds were present.

The lines in Figure 2 are fits to the data using cubic splines weighted by observational errors. Larger weights were given to the $UBVRI$ fitting, while relatively small weights were given to the JKH fitting. In this fitting procedure, we combined our own data (*filled circles*) with other B and H data

(*open circles*) reported in the IAU Circulars and Gal-Yam et al.'s (2002) I data (*crosses*) from the Wise Observatory. Except for the I band, for which we have no data before February 14, we could obtain light curves covering the entire period using only our own data.

The date and magnitude of the epoch of peak brightness were determined from the spline curve for each of $UBVRIJHK$. The uncertainty of the epoch of maximum was defined as the range of epochs in which the magnitude is fainter than the peak magnitude by no more than 0.01 mag. The results are shown in Table 2. These peak dates agree well with those derived previously by Gal-Yam et al. (2002).

The wavelength-dependent slope of the declining part of the light curve, dm_λ/dt (mag day $^{-1}$), was also determined. These results are also given in Table 2.

3. BOLOMETRIC LIGHT CURVE

Bolometric light curves of SNe are very valuable for constructing theoretical models. Our photometric data, covering from U to K , enable us to build the bolometric light curve for SN 2002ap. For days when data in one or two bands are not available from MAGNUM measurements, we interpolated the data taken on adjacent dates from MAGNUM and other sources (Gal-Yam et al. 2002; IAUcs and VSNET).⁹

⁹ Additional information is available at <http://vsnet.kusastro.kyoto-u.ac.jp/vsnet/SNe/sn2002ap.html>.

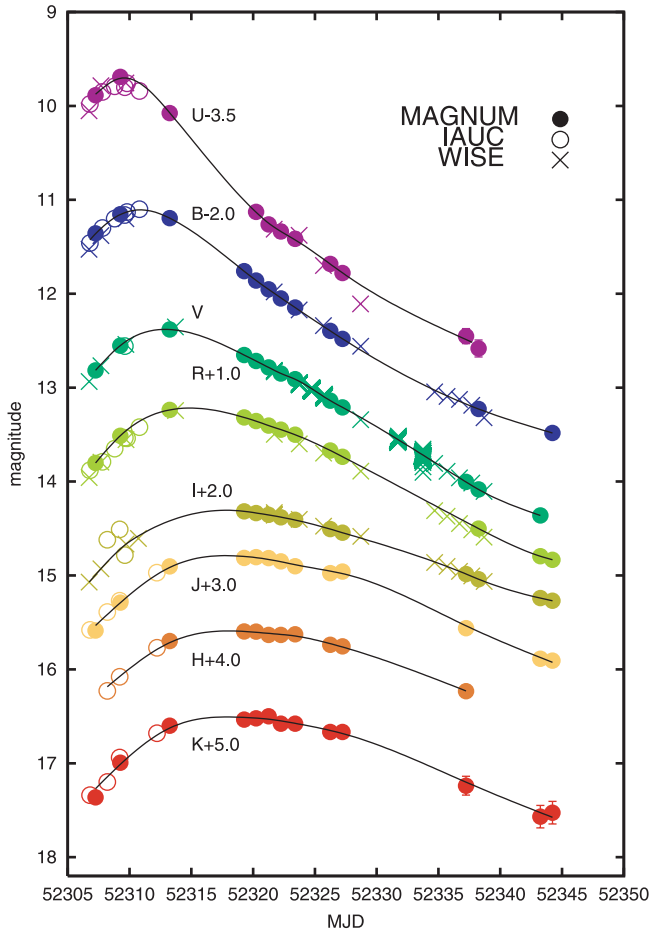


FIG. 2.—Multiband light curves of SN 2002ap in the *UBVRIJHK* bands for the observations before solar conjunction. The magnitude scales are shifted vertically in order to avoid overlap. Filled circles show our data, and other symbols show the data reported by other authors (*open circles*: Mattila, Meikle, & Chambers 2002; Hasubick & Hornoch 2002; Motohara et al. 2002; Riffeser, Goessl, & Ries 2002; Szokoly 2002; *crosses*: Gal-Yam et al. 2002). The error in each band corresponds to the combined uncertainty in calibrating the magnitude of SN 2002ap and the reference star (*UBVRI*) or standard stars (*JHK*). The errors for March 4–11 are larger, as thin patchy clouds were present. Solid lines are cubic splines fitted mostly to our data weighted by observational errors. See the text for details of the fitting procedure.

First, all *UBVRIJHK* magnitudes were converted into absolute monochromatic fluxes. Various sets of conversion factors for the standard system are available in the literature. As differences between these various sets are marginal, we adopted the values recently compiled by Bessell (2001). We adopted a combined Galaxy M74 reddening of $E(B-V) = 0.09 \pm 0.01$, as determined from the Na I D equivalent widths in a high-resolution spectrum (Takada-Hidai, Aoki, & Zhao 2002), and a distance modulus $m - M = 29.5^{+0.1}_{-0.2}$, combining the estimates of Sharina et al. (1996) and Sohn & Davidge (1996) from the brightest supergiants.

Monochromatic fluxes were then integrated over frequency with a cubic spline interpolation technique. Those on February 8 are plotted in Figure 3 as an example. We assumed zero flux at both integral limits, i.e., at the blue edge of the *U* band and at the red edge of the *K* band. The errors introduced by this assumption are much less than 10%. An early UV flux between 245 and 320 nm was mea-

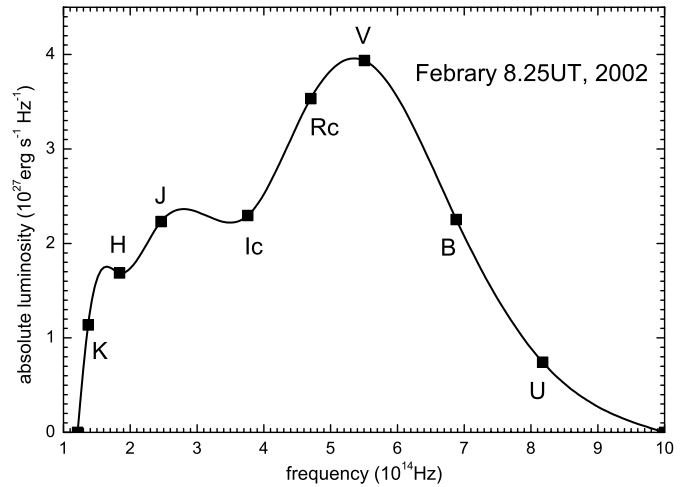


FIG. 3.—Monochromatic flux distribution (*squares*) of SN 2002ap on February 8, constructed using MAGNUM *UBVRIJHK* photometry, and the cubic spline fitting curve (*solid line*).

sured with *XMM-Newton* on February 3 (Soria & Kong 2002). Extending the integration to this band, we found it contributes only 4% of the total flux. The NIR flux, on the other hand, accounts for a significant fraction of the total flux, ranging from 20% on February 2 to 40% on March 10 and being around 20% in June. This highlights the importance of *JHK* photometry.

Uncertainty in the bolometric light curve also comes from the nonstellar nature of SN spectra, which are dominated by very broad lines. The true bolometric flux can be obtained only from spectrophotometry. We compared our results with the model UV-optical-NIR spectrophotometry derived from the best-fit synthetic Monte Carlo spectra of Mazzali et al. (2002) and found that the differences between the two data sets are less than 0.2 mag. The total uncertainty in our bolometric light curve, including the uncertainty in the distance modulus, is therefore estimated to be $\lesssim 0.3$ mag.

We list in Table 3 our bolometric magnitudes, M_{bol} , along with the bolometric corrections (BC), $\text{BC} \equiv M_{\text{bol}} - M_V$. They are shown in Figure 4 as filled circles. We adopted an explosion date of January 28 (Mazzali et al. 2002). We also plot the spectrophotometric point on January 30 as an open circle and four unfiltered CCD magnitude points taken within 1 day of the discovery (Nakano et al. 2002; VSNET) as crosses. These roughly define the very early phase of the bolometric light curve.

4. DISCUSSION

4.1. Comparison with Other Hypernovae

The multiband light curves of SN 2002ap are narrower than those of the well-studied Type Ic hypernovae SNe 1998bw and 1997ef. This is shown in Figure 4, where the bolometric light curve of SN 1998bw (Patat et al. 2001), shifted down by 1.85 mag for the sake of comparison, and that of SN 1997ef (Mazzali, Iwamoto, & Nomoto 2000) are plotted as open circles and filled stars, respectively. The light curve of SN 2002ap declines more rapidly after peak, indicating that the trapping of γ -rays released in the $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ decays is less efficient in SN 2002ap

TABLE 1
DATA OF LIGHT CURVES OF SN 2002ap

UT	MJD	m_U	m_B	m_V	m_R	m_I	m_J	m_H	m_K	Weather
Feb 2.25	52,307.25	13.39 ± 0.05	13.36 ± 0.02	12.82 ± 0.01	12.80 ± 0.02		12.59 ± 0.04		12.36 ± 0.06	Clear
Feb 4.25	52,309.25	13.19 ± 0.05	13.15 ± 0.02	12.55 ± 0.01	12.51 ± 0.02		12.29 ± 0.04		11.99 ± 0.05	Clear
Feb 8.25	52,313.25	13.58 ± 0.05	13.20 ± 0.02	12.38 ± 0.01	12.24 ± 0.02		11.90 ± 0.02	11.70 ± 0.03	11.60 ± 0.03	Clear
Feb 14.27	52,319.27		13.76 ± 0.02	12.65 ± 0.01	12.32 ± 0.02	12.32 ± 0.01	11.81 ± 0.03	11.60 ± 0.02	11.53 ± 0.03	Clear
Feb 15.25	52,320.25	14.63 ± 0.06	13.86 ± 0.02	12.72 ± 0.01	12.36 ± 0.02	12.34 ± 0.01	11.82 ± 0.02	11.60 ± 0.03	11.52 ± 0.02	Clear
Feb 16.25	52,321.25	14.76 ± 0.06	13.95 ± 0.02	12.78 ± 0.01	12.40 ± 0.02	12.35 ± 0.01	11.82 ± 0.02	11.63 ± 0.02	11.50 ± 0.03	Clear
Feb 17.25	52,322.25	14.84 ± 0.07	14.05 ± 0.02	12.85 ± 0.01	12.45 ± 0.02	12.38 ± 0.01	11.85 ± 0.02	11.63 ± 0.02	11.58 ± 0.04	Clear
Feb 18.4	52,323.40	14.92 ± 0.07	14.15 ± 0.02	12.91 ± 0.01	12.50 ± 0.02	12.41 ± 0.01	11.90 ± 0.02	11.63 ± 0.02	11.58 ± 0.02	Clear
Feb 21.24	52,326.24	15.18 ± 0.05	14.40 ± 0.02	13.14 ± 0.01	12.67 ± 0.02	12.51 ± 0.01	11.98 ± 0.03	11.74 ± 0.03	11.67 ± 0.05	Clear
Feb 22.24	52,327.24	15.28 ± 0.05	14.48 ± 0.02	13.21 ± 0.01	12.74 ± 0.02	12.55 ± 0.01	11.96 ± 0.02	11.76 ± 0.04	11.67 ± 0.03	Clear
Mar 4.23	52,337.23	15.95 ± 0.08		14.00 ± 0.01		12.98 ± 0.01	12.56 ± 0.06	12.23 ± 0.05	12.24 ± 0.37	Thin cloud
Mar 5.24	52,338.24	16.08 ± 0.09	15.23 ± 0.02	14.08 ± 0.01	13.50 ± 0.02	13.04 ± 0.01				Thin cloud
Mar 10.24	52,343.24			14.36 ± 0.01	13.80 ± 0.02	13.24 ± 0.01	12.89 ± 0.06		12.57 ± 0.08	Thin cloud
Mar 11.23	52,344.23		15.48 ± 0.04		13.83 ± 0.02	13.27 ± 0.01	12.91 ± 0.06		12.53 ± 0.12	Thin cloud
Jun 12.61	52,437.61			16.14 ± 0.03					15.01 ± 0.07	Clear
Jun 13.60	52,438.60		16.78 ± 0.04				15.72 ± 0.06	14.90 ± 0.06		Clear
Jun 14.60	52,439.60				15.41 ± 0.03					Clear
Jun 16.60	52,441.60					15.08 ± 0.04				Clear
Jun 18.60	52,443.60					15.12 ± 0.03		15.05 ± 0.06		Clear

NOTE.—Apparent magnitudes were measured within the aperture size of 11", but a smaller aperture was adopted to enhance the S/N ratio for the U -band images taken on March 4–5 (8^h3) and the images taken in June (5^h5 for $BVRi$; 8^h3 for JHK).

TABLE 2
CHARACTERISTICS OF LIGHT CURVES OF SN 2002ap

Item	U Band	B Band	V Band	R Band	I Band	J Band	H Band	K Band
Peak Feb date (UT)	4.6 ± 2	6.0 ± 1	7.9 ± 2	9.9 ± 1	12.7 ± 2	12.9 ± 2	13.0 ± 2	12.9 ± 2
Peak date (MJD)	52,309.6 ± 2	52,311.0 ± 1	52,312.9 ± 2	52,314.9 ± 1	52,317.7 ± 2	52,317.9 ± 2	52,318.0 ± 2	52,317.9 ± 2
Peak apparent magnitude	13.20	13.11	12.38	12.22	12.31	11.79	11.59	11.51
Peak absolute magnitude	−16.30	−16.39	−17.12	−17.28	−17.19	−17.71	−17.91	−17.99
Gradient (mag day ^{−1})	0.08 ± 0.01	0.08 ± 0.01	0.08 ± 0.01	0.07 ± 0.01	0.04 ± 0.01	0.06 ± 0.01	0.05 ± 0.01	0.06 ± 0.01

NOTE.—Peak date and apparent magnitude in each band are determined from the cubic spline fitting to the data. Peak absolute magnitude is based on the distance modulus $m - M = 29.5$ mag; see Sharina et al. 1996 and Sohn & Dvige 1996. The decline rate in each band was determined from linear fitting to the data taken well after the peak date (February 16–March 5 for U and V , February 15–March 5 for B , February 21–March 5 for R , and I , February 22–March 5 for J , H , and K).

TABLE 3

BOLOMETRIC MAGNITUDES OF SN 2002ap AND BOLOMETRIC CORRECTIONS

UT	MJD	M_{bol}	Bolometric Correction
Feb 2.25	52,307.25	-16.50	0.45
Feb 4.25	52,309.25	-16.77	0.45
Feb 8.25	52,313.25	-16.90	0.49
Feb 14.27	52,319.27	-16.72	0.40
Feb 15.25	52,320.25	-16.68	0.37
Feb 16.25	52,321.25	-16.64	0.35
Feb 17.25	52,322.25	-16.60	0.32
Feb 18.40	52,323.40	-16.54	0.32
Feb 21.24	52,326.24	-16.39	0.24
Feb 22.24	52,327.24	-16.35	0.21
Mar 4.23	52,337.23	-15.74	0.03
Mar 10.24	52,343.24	-15.42	-0.01
Mar 11.23	52,344.23	-15.40	0.01
Jun 13.6	52,438.60	-13.52	0.11

and that the radiation generated by trapped γ -rays can escape more easily. This suggests that the ejecta of SN 2002ap are less massive.

Figure 4 also shows that SN 2002ap was about 1.8 mag fainter than SN 1998bw at peak and about as bright as SN 1997ef. The brightness of the bolometric peak, ~ -16.9 mag, and its epoch, approximately day 11, are similar to those of SN 1994I (Nomoto et al. 1994). This indicates that a similar amount of ^{56}Ni , $\sim 0.07 M_{\odot}$, was produced by the two SNe, as suggested by theoretical models (Mazzali et al. 2002). SN 2002ap is not as powerful an explosion as SN 1998bw, which ejected $\sim 0.4\text{--}0.7 M_{\odot}$ of ^{56}Ni (Nakamura et al. 2001), but rather more similar to SN 1997ef, which ejected $\sim 0.1 M_{\odot}$.

Figure 5 shows a comparison of the colors of SN 2002ap with those of SN 1997ef. In the figure, the time axes of SNe 1998bw and 1997ef are compressed by a factor of 1.5, which

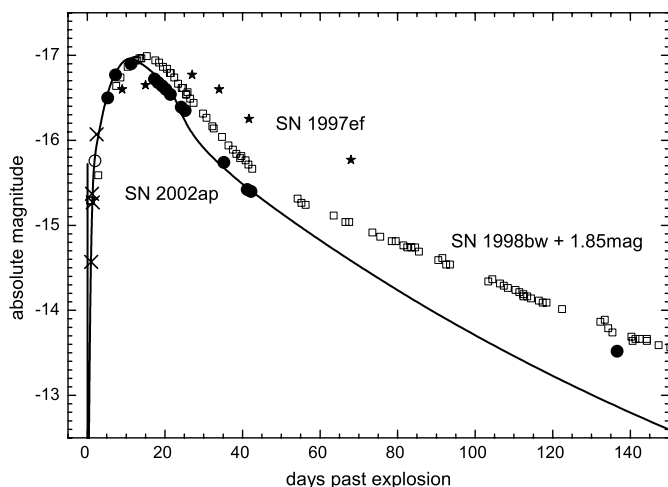


FIG. 4.—Bolometric light curve of SN 2002ap, constructed using MAGNUM *UBVRIJK* photometry (filled circles), compared with the synthetic light curve obtained from a model of a spherically symmetric explosion with $M_{\text{ej}} = 2.5 M_{\odot}$ and $E_K = 4 \times 10^{51}$ ergs (solid line). Also shown are one spectrophotometric point based on a Monte Carlo synthetic spectrum for a date earlier than MAGNUM's first data point (open circle) and four early unfiltered CCD magnitude points (crosses). Open squares show the bolometric light curve of SN 1998bw (Patat et al. 2001) shifted down by 1.85 mag, and filled stars are the bolometric light curve of SN 1997ef (Mazzali, Iwamoto, & Nomoto 2000).

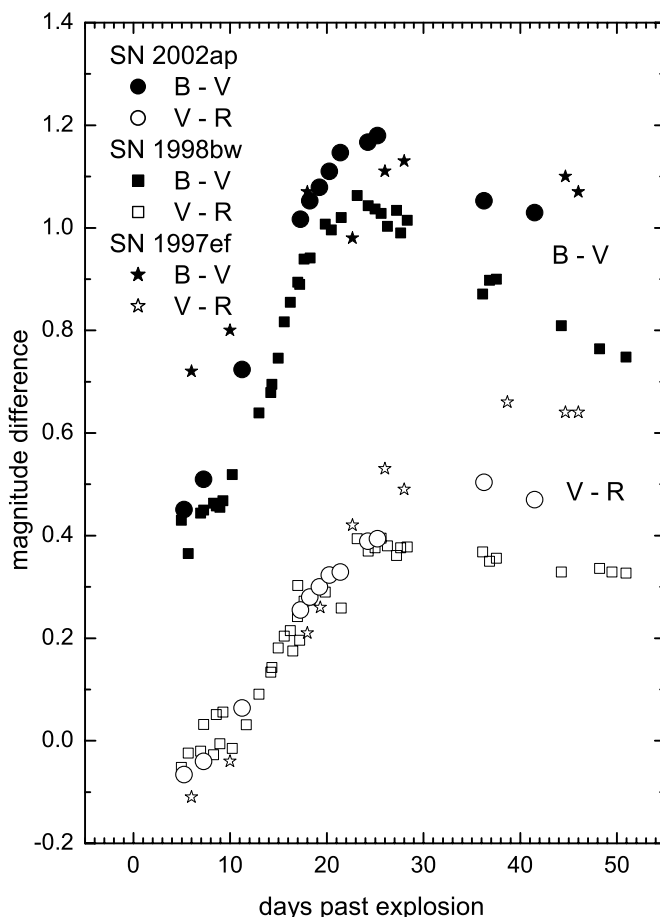


FIG. 5.—Evolution of $B-V$ and $V-R$ of the three Type Ic supernovae: SNe 2002ap, 1998bw, and 1997ef. The time axes of SNe 1998bw and 1997ef are shortened by a factor of 1.5. The data of SN 1998bw are calculated from the photometry of Patat et al. (2001), and those of SN 1997ef are evaluated from the spectra of Mazzali et al. (2000).

clearly shows that SN 2002ap evolves about 1.5 times faster than SNe 1998bw and 1997ef in terms of colors. This is in agreement with the finding by Kinugasa et al. (2002) that the evolution of the spectra of SN 2002ap proceeds at about 1.5 times the rate of SN 1997ef, which again suggests that SN 2002ap ejected less material than SNe 1998bw and 1997ef.

4.2. NIR Light Curves

Our NIR photometry is the most intensive for any Type Ic SN.

In Figure 6 we compare the absolute $JHK(K')$ light curves of SN 2002ap with those of the other four Type Ic SNe with published NIR photometry. These are SNe 1983I (Elias et al. 1985), 1983V (Clocchiatti et al. 1997), 1994I (Rudy et al. 1994; Grossan et al. 1999), and 1998bw (Patat et al. 2001). Among these, the hypernova SN 1998bw stands out for being about 1.5 mag brighter. The J -band light curve of SN 1983V is significantly broader than that of SN 2002ap, consistent with its designation as a “slow” Type Ic in the optical (Clocchiatti et al. 1997). For the otherwise well-observed SN 1994I, there is only one data point in each of J and H and two in K' . These show that the NIR light curves of SN 1994I were probably much narrower than those of SN 2002ap. The data of SN 1983I seem to connect

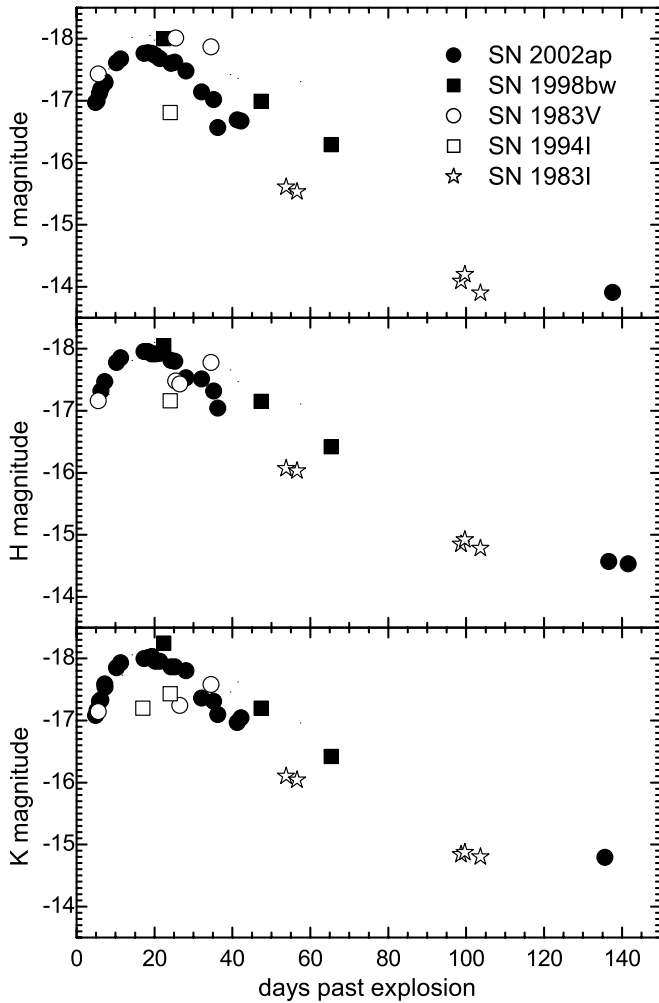


FIG. 6.—Comparison of the *J* (top), *H* (middle), and *K* (bottom) light curves in absolute magnitudes of the five Type Ic SNe: 2002ap, 1998bw, 1983V, 1994I, and 1983I.

smoothly with those of SN 2002ap before day 50 and after day 130, but this may be the result of our arbitrarily assigning the epochs.

Better understanding of the *JHK* photometry of Type Ic SNe and hypernovae requires theoretical modeling in the NIR, which is beyond the scope of this paper.

4.3. Comments on Theoretical Models

Based on spectrum synthesis, Mazzali et al. (2002) have proposed as a viable model for SN 2002ap the energetic spherical explosion of a C + O star, ejecting $2.5\text{--}5 M_{\odot}$ of material with a kinetic energy of $(4\text{--}10) \times 10^{51}$ ergs. Their favorite model is one with $M_{\text{ej}} = 2.5 M_{\odot}$ and $E_K = 4 \times 10^{51}$ ergs. This is the explosion of a $5 M_{\odot}$ C + O star, leaving a compact remnant of mass $M_{\text{rem}} = 2.5 M_{\odot}$, possibly a black hole. Such a C + O star is formed in a He core of mass $M_{\alpha} = 7.0 M_{\odot}$, corresponding to a main-sequence mass $M_{\text{ms}} \approx 20\text{--}25 M_{\odot}$. The light curve obtained from this model, which is shown in Figure 4 as a solid line, fits the bolometric light curve very well before day 50.¹⁰

¹⁰ The model light curve in the first day shown in Fig. 4 of Mazzali et al. (2002) is in disagreement with the early unfiltered photometry. That was caused by a numerical error and has been corrected.

However, the model light curve deviates from the observations at later phases, lying 0.7 mag above the bolometric point in June. This suggests that the γ -ray optical depth at later phases may be underestimated by the Mazzali et al. (2002) model. A similar problem occurred in the case of SN 1998bw, where the models that best reproduce the observed light curve near the peak underestimate its brightness around day 150 (Nakamura et al. 2001) by ~ 1 mag. Maeda et al. (2003) recently proposed a general parameterized two-component ejecta model and successfully reproduced the light curves of SNe 1998bw and 2002ap at both peak and later phases. They suggested that the denser inner component introduced to increase the γ -ray optical depth at later phases is the natural outcome of jet-driven hypernovae explosions (Maeda et al. 2002).

Höflich, Wheeler, & Wang (1999) introduced aspherical but low-energy and low-mass ejecta to reproduce the light curve of SN 1998bw. In fact, it is not difficult to find low-energy solutions, aspherical or spherical, for hypernova light curves by decreasing the mass of the ejecta (e.g., Iwamoto et al. 1998). However, we must emphasize that it is the unusually broad spectral features that make hypernovae distinct from normal SNe and that these strongly require high kinetic energies in both spherical models (Iwamoto et al. 1998) and aspherical ones (Maeda et al. 2002). It is unclear whether the low-energy model of Höflich et al. (1999) can reproduce the broad lines in SN 1998bw. Wang et al. (2003) also warned that very broad line features might have been observed in the spectra of other Type Ib/Ic SNe, so far classified as normal, if they had been observed at a time as early as SN 2002ap. Obviously, future early observations are necessary to verify this speculation.

As for SN 2002ap, Wang et al. (2003) interpreted the weak polarization in SN 2002ap as the result of an asymmetry ($\sim 10\%$) in the ejecta. Spectropolarimetry was also obtained by Kawabata et al. (2002) and Leonard et al. (2002) at somewhat later epochs. Their estimate of the degree of asymmetry is similar, and they discovered an intriguingly fast evolution of the polarization angle. Our estimate of the kinetic energy of SN 2002ap may change if asymmetry is introduced. In the case of SN 1998bw, concentrating the kinetic energy along the line of sight led Maeda et al. (2002) to reduce its value to 10×10^{51} ergs. However, Wang et al. (2003) suggested that SN 2002ap is likely viewed near the equatorial plane, unlike SN 1998bw. In the aspherical models of Maeda et al. (2002), this would actually lead to a larger, not a smaller, kinetic energy. In any case, we do not expect that the degree of asphericity, about 10%–20%, will significantly affect the global values derived in spherical symmetry.

Berger, Kulkarni, & Chevalier (2002) claimed that the Mazzali et al. (2002) model places some 10^{48} ergs of kinetic energy at $v > 10^5 \text{ km s}^{-1}$, which is too large, considering the weak radio emission observed. We note, however, that Mazzali et al. (2002) constructed their model by fitting the optical observations, and hence the density structure they used only extended up to $60,000 \text{ km s}^{-1}$. It is therefore not justified to extrapolate it to above $v > 10^5 \text{ km s}^{-1}$, where the material has too low a density to make an observable contribution to the optical spectra and light curves, except for polarimetry (Kawabata et al. 2002).

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