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A flattening in the optical light curve of SN 2002ap

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ABSTRACT

We present the $UBVR_cI_c$ broad-band optical photometry of the type Ic supernova SN 2002ap obtained during 2002 February 6–March 23 in the early decline phases and also later on 2002 August 15. Combining these data with the published ones, the general light-curve development is studied. The time and luminosity of the peak brightness and the peak width are estimated. There is a flattening in the optical light curve about 30 d after the B maximum. The flux decline rates before flattening are 0.127 ± 0.005, 0.082 ± 0.001, 0.074 ± 0.001, 0.062 ± 0.001 and 0.040 ± 0.001 mag d^{-1} in U, B, V, R_c and I_c passbands respectively, while the corresponding values after flattening are about 0.02 mag d^{-1} in all the passbands. The maximum brightness of SN 2002ap, $M_V = -17.2$ mag, is comparable to that of the type Ic 1997ef, but fainter than that of the type Ic hypernova SN 1998bw. The peak luminosity indicates an ejection of $\sim 0.06\,\mathrm{M}_{\odot}$ ^{56}Ni mass.

We also present low-resolution optical spectra obtained during the early phases. The Si II absorption minimum indicates that the photospheric velocity decreased from $\sim$21 360 km s^{-1} to $\sim$10 740 km s^{-1} during a period of $\sim$6 d.

Key words: techniques: photometric – techniques: spectroscopic – supernovae: general – supernovae: individual: SN 2002ap.

1 INTRODUCTION

The supernova SN 2002ap ($\alpha_{2000} = 01^{\mathrm{h}}36^{\mathrm{m}}23\overset{\mathrm{s}}{.}92$; $\delta_{2000} = +15°45'13\overset{''}{.}3$) was discovered on 2002 January 29.4 UT by Y. Hirose at $V \sim 14.5$ mag, in the outer region of the nearby spiral M74 (Nakono et al. 2002). Low-resolution spectra of SN 2002ap obtained during 2002 January 30–31 (Kinugasa et al. 2002a,b; Meikle et al. 2002; Filippenko & Chornock 2002) were similar to those of type Ic supernovae. However, the spectral features were found to be extremely broad resembling the type Ic 'hypernovae' SN 1997ef and SN 1998bw (Filippenko 1997; Nomoto et al. 2001; Mazzali et al. 2002).

At a distance of 7.3 Mpc, SN 2002ap being the nearest hypernova discovered to date, was a good target for a detailed monitoring, and has been subject to multi-wavelength observations. In addition to optical observations, it has been observed in the X-ray (Sutaria et al. 2003), radio (Berger, Kulkarni & Chevalier 2002; Sutaria et al. 2003) and in the infrared (Mattila & Meikle 2002). Evidence for a high-velocity asymmetric explosion has been indicated by spectropolarimetric observations (Kawabata et al. 2002; Leonard et al. 2002; Wang et al. 2003).

The broad spectral features in the spectrum and the evolution of Si II spectral line indicate a high expansion velocity ($\sim$30 000 km s^{-1}), which supports hypernova model for the SN 2002ap (Kinugasa et al. 2002b; Meikle et al. 2002; Gal-Yam & Shemmer 2002a; Gal-Yam, Ofek & Shemmer 2002b; Filippenko & Chornock 2002). The spectropolarimetric observations during the early phase indicate a similarity with SN 1998bw (Leonard et al. 2002). Modelling of the optical observations indicate SN 2002ap as an energetic event, with an explosion energy of $\simeq$4–10 $\times$ 10^{51} erg (Mazzali et al. 2002). However, the radio observations seem to indicate that SN 2002ap an ordinary type Ic supernova, without a jet (Berger et al. 2002). A study of the $UBVRIH_{\alpha}K$ images of galaxy M74 obtained several years prior to the discovery of SN 2002ap (Smartt et al. 2002) resulted in a non-detection of the progenitor.

The spectral similarity to SN 1998bw, the possible link between very energetic supernova and gamma-ray bursts and the lack of substantive data on rare type Ic SN events make SN 2002ap very important object to study in detail. We have therefore carried out dense temporal multi-colour optical photometric observations during the early phases. These in combination with the published data are used to study the development of the optical light curve. Our

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observations are the first to indicate a flattening in the light curve of the SN 2002ap about 30 d after the B maximum. We also present low-resolution optical spectra obtained during the early phases. The details of both photometric and spectroscopic observations are presented in the next section, while the development of the light curves, spectral and other properties of the SN 2002ap are discussed in the remaining part of the paper.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Photometry

During the early phase, optical $UBVR_cI_c$ observations of SN2002ap were carried out for 32 d between 2002 February 6 and March 23 from the State Observatory, Nainital, India using a 2048 × 2048 pixel CCD system attached at the f/13 Cassegrain focus of the 104-cm Sampurnanand reflector. One pixel of the CCD chip corresponds to a square of ∼0.38 arcsec while the entire chip covers a field of 13 × 13 arcmin^2 on the sky. The gain and read-out noise of the CCD camera are 10 e$^-$ ADU^{-1} and 5.3 e$^-$ respectively. The supernova was observed in the BVR_cI_c bands during most of the nights, while U band observations could be obtained only for three nights. Exposure times for most of the U, B, V, R_c and I_c band images were 300, 100, 100, 60 and 60 s respectively. The observations of SN 2002ap could not be carried out during 2002 April to July due to its proximity to the sun as well as rainy sky conditions in India. SN2002ap was however observed on 2002 August 15 in VR_cI_c bands using the SITe 1024 × 1024 pixel CCD system at the Cassegrain focus of the 2-m Himalayan Chandra Telescope at the Indian Astronomical Observatory, Hanle, India. Two frames, each with exposure time of 420 s, were obtained in V; three frames, with exposure times of 300, 420 and 540 s were obtained in R_c and three frames, each with an exposure time of 300 s were obtained in I_c. Several bias and twilight flat frames were obtained by the both CCD cameras to calibrate the supernova images using standard techniques. Data reduction was carried out using IRAF[1] and MIDAS softwares. For photometric calibration, comparison stars 1 and 2 of Gal-Yam et al. (2002b) were observed along with SN 2002ap. The magnitudes of SN 2002ap and the comparison stars were estimated using a fixed aperture photometry. Since SN 2002ap is located in the outer region of M74, the contamination due to the light of the galaxy is expected to be negligible in the measurements (Smartt et al. 2002). The zero-point accuracy of the $UBVR_cI_c$ magnitudes is of order 0.02 mag. In order to use the observations made during non-photometric sky conditions, differential photometry has been adopted, assuming that the errors introduced due to colour differences between comparison stars and SN 2002ap are much smaller than the zero-point errors.

Following the calibration provided by Henden (2002), we have used $U = 14.10$ mag, $B = 13.84$ mag, $V = 13.06$ mag, $R_c = 12.61$ mag, $I_c = 12.14$ mag for star 1 and $U = 14.40$ mag, $B = 14.33$ mag, $V = 13.69$ mag, $R_c = 13.32$ mag, $I_c = 12.95$ mag for comparison star 2. The differences in the measured BVR_cI_c magnitudes of the two comparison stars do not show any secular trend during our observations. The standard deviation of these differences are 0.013, 0.026, 0.033 and 0.020 mag in the B, V, R_c and I_c passbands respectively, indicating the level of accuracy of our photometry. The photometric errors in the U band are higher, of order 0.04 mag. As the comparison stars are located in much cleaner environments than SN 2002ap, farther from the nucleus of M74, their photometry can be considered to be more accurate than that of SN 2002ap. The $UBVR_cI_c$ magnitudes of the SN 2002ap estimated based on our observations are tabulated in Table 1 along with errors.

2.2 Spectroscopy

Spectroscopic observations of SN 2002ap were made from the Vainu Bappu Observatory, Kavalur, India, on 2002 February 3.61, 4.60, 5.60 and 10.59 UT. CCD spectra, in the range 3800–8000 Å, were obtained using the OMR spectrograph on the 2.3-m Vainu Bappu Telescope. The spectra were obtained at a resolution of 600 on February 3 and 4, while the spectra of February 5 and 10 were obtained at a resolution of 1200. All spectra were obtained with a narrow slit of 2 arcsec width aligned at 0° PA. Spectrophotometric standard HD 19445 was observed on February 3, while Hiltner 600 was observed on all other nights. Both standards were observed with a slit of 5 arcsec width.

All spectra were bias subtracted, flat-field corrected, extracted and wavelength calibrated in the standard manner using the IRAF reduction package. The spectra were corrected for instrumental response, telluric absorption lines and brought to a relative flux scale using the spectrophotometric standard observed on the same night. The fluxes have been brought to an absolute flux scale using zero-points derived from $UBVR_cI_c$ photometry.

3 DISTANCE AND REDDENING

Interstellar Na I D1 absorption features due to the gas in M74 indicate a reddening of $E(B - V) = 0.008 \pm 0.002$ mag due to the host galaxy (Klose, Guenther & Woitas 2002). The Galactic extinction estimated from Schlegel, Finkbeiner & Davis (1998) is $E(B - V) = 0.07$ mag. Thus the galactic extinction clearly dominates the total extinction of $E(B - V) = 0.08$ mag. The extinction in different passbands corresponding to this reddening are calculated using the relations given by Cardelli, Clayton & Mathis (1989) for normal interstellar reddening. The values thus obtained are listed in Table 2.

There is no Cepheid distance determination to M74. Most of the SN 2002ap studies have used the mean distance of 8 Mpc for M74 group derived by Sharina, Karachentsev & Tikhonov (1996), except Smartt et al. (2002) who used a distance of 7.3 Mpc for M74. As the difference between these two values corresponds to a difference of 0.2 mag in distance modulus and does not have a significant effect on the conclusions drawn in the paper, we have used a distance of 7.3 Mpc for M74. In the light of the above, we conclude that distance modulus of M74 has an uncertainty of about 0.2 mag while the total reddening is uncertain by ±0.01 mag.

4 DESCRIPTION OF SPECTRA

Fig. 1 shows the spectra of SN 2002ap. Offsets of 4.5, 3.5, and 1.7 in flux units have been added to the spectra of February 3.61, 4.60 and 5.60 respectively. The lines in the spectra have been identified following Mazzali et al. (2002). The spectra presented here fill in the gap in the pre-maximum phase observations presented by Mazzali et al. (2002) and Kinugasa et al. (2002b). Following Kinugasa et al. (2002b), we estimate the photospheric velocity using the Si II 6347, 6371 Å (6355 Å) absorption minimum. Not much variation is detected in the photospheric velocity for the spectra of February 3.61, 4.60 and 5.60, corresponding to −2.38, −1.39, −0.48 d from B maximum. The average of all three spectra gives a value of 21, 360 ± 2000 km s^{-1}, corresponding to day −1.39 from

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Table 1. *UBVR*$_c$ and I_c magnitudes of SN 2002ap along with errors, Julian date and mid UT of observations are listed.

Date (UT)	Time in JD	I_c (mag)	R_c (mag)	V (mag)	B (mag)	U (mag)
Feb 06.62	2452312.12	12.46 ± 0.02	12.39 ± 0.04	12.42 ± 0.03	13.12 ± 0.02	–
Feb 07.61	2452313.11	12.42 ± 0.03	12.33 ± 0.03	12.42 ± 0.03	13.16 ± 0.03	–
Feb 09.66	2452315.16	12.29 ± 0.02	12.25 ± 0.03	12.42 ± 0.03	13.29 ± 0.03	–
Feb 12.66	2452318.15	12.26 ± 0.03	12.31 ± 0.03	12.53 ± 0.03	13.58 ± 0.02	–
Feb 13.58	2452319.08	–	–	12.60 ± 0.03	13.70 ± 0.02	–
Feb 14.57	2452320.07	12.28 ± 0.04	12.38 ± 0.03	12.61 ± 0.04	13.80 ± 0.02	14.64 ± 0.02
Feb 16.64	2452322.14	–	12.45 ± 0.04	12.77 ± 0.03	13.97 ± 0.02	–
Feb 17.63	2452323.13	–	–	12.86 ± 0.03	14.04 ± 0.03	–
Feb 18.58	2452324.08	12.40 ± 0.03	12.58 ± 0.03	12.92 ± 0.03	14.17 ± 0.02	15.12 ± 0.02
Feb 21.58	2452327.08	12.50 ± 0.02	12.74 ± 0.03	13.14 ± 0.03	14.41 ± 0.02	–
Feb 23.57	2452329.07	12.56 ± 0.02	12.87 ± 0.03	13.29 ± 0.03	14.59 ± 0.02	–
Feb 24.60	2452330.10	12.62 ± 0.02	12.93 ± 0.03	13.38 ± 0.03	14.65 ± 0.02	–
Feb 25.56	2452331.06	12.68 ± 0.03	13.00 ± 0.03	13.45 ± 0.03	14.74 ± 0.02	–
Feb 26.58	2452332.08	12.72 ± 0.02	13.06 ± 0.04	13.52 ± 0.03	14.79 ± 0.02	16.10 ± 0.12
Feb 27.58	2452333.08	12.76 ± 0.02	13.12 ± 0.03	13.60 ± 0.03	14.86 ± 0.02	–
Feb 28.59	2352334.10	12.79 ± 0.03	13.18 ± 0.03	13.64 ± 0.03	14.94 ± 0.02	–
Mar 03.58	2452337.08	12.92 ± 0.02	13.41 ± 0.03	13.91 ± 0.03	15.10 ± 0.02	–
Mar 04.58	2452338.08	13.01 ± 0.02	13.48 ± 0.03	13.99 ± 0.03	15.20 ± 0.02	–
Mar 05.58	2452339.08	13.04 ± 0.02	13.56 ± 0.03	14.07 ± 0.03	15.25 ± 0.02	–
Mar 06.57	2452340.07	13.08 ± 0.02	13.62 ± 0.03	14.14 ± 0.03	15.28 ± 0.02	–
Mar 07.60	2452341.01	13.17 ± 0.03	13.67 ± 0.04	–	–	–
Mar 08.57	2452342.07	13.20 ± 0.02	13.74 ± 0.03	14.26 ± 0.03	15.40 ± 0.02	–
Mar 09.57	2452343.07	13.24 ± 0.03	13.77 ± 0.03	14.30 ± 0.03	15.38 ± 0.03	–
Mar 10.57	2452344.07	13.26 ± 0.02	13.84 ± 0.03	14.32 ± 0.03	15.48 ± 0.03	–
Mar 11.57	2452345.07	13.32 ± 0.02	13.87 ± 0.03	14.38 ± 0.03	15.49 ± 0.03	–
Mar 13.57	2452347.07	13.33 ± 0.02	13.94 ± 0.03	14.46 ± 0.03	15.55 ± 0.02	–
Mar 14.58	2452348.08	13.38 ± 0.02	–	14.48 ± 0.03	15.58 ± 0.02	–
Mar 15.58	2452349.08	–	13.97 ± 0.03	14.53 ± 0.03	15.62 ± 0.04	–
Mar 16.58	2452350.08	13.41 ± 0.02	13.98 ± 0.03	14.55 ± 0.03	15.55 ± 0.14	–
Mar 17.58	2452351.08	13.41 ± 0.03	14.03 ± 0.03	14.54 ± 0.04	–	–
Mar 18.58	2452352.08	–	14.07 ± 0.04	–	–	–
Mar 23.57	2452357.07	–	14.14 ± 0.05	–	–	–
Aug 15.90	2452502.40	16.37 ± 0.03	16.46 ± 0.03	17.32 ± 0.03	–	–

B maximum, or 6.7 d since explosion. Date of explosion is assumed to be 2002 January 28.9 UT 2002 (Mazzali et al. 2002). The velocity decreased to a value of 10, 740 ± 1500 km s^{-1} on February 10.59, 4.60 d after *B* maximum, or 12.69 d since explosion. These estimates are in excellent agreement with the velocity evolution estimate by Kinugasa et al. (2002b) for SN 2002ap.

5 THE UBVR$_c$I$_c$ LIGHT CURVE AND ITS DEVELOPMENT

In order to produce temporally dense light curves in *UBVR*$_c$$I_c$, we have combined our observations with published ones, taking data from Gal-Yam et al. (2002b), Borisov et al. (2002), Yoshii et al. (2002), Matohara et al. (2002), Riffeser, Goessl & Ries (2002), Hornoch & Lelekovice (2002), Henden et al. (2002). The frequency distribution of the data taken from the literature is $N(U, B, V, R_c, I_c) = (18, 28, 24, 33, 27)$. The combined *UBVR*$_c$$I_c$ light curves during the early phase are shown in Fig. 2. A good agreement can be clearly seen in the different data sets indicating that, within observational errors, they are on the same photometric scale.

5.1 First 60 d

Fig. 2 indicates that the light curve of SN 2002ap rose fast but declined slowly in an exponential manner. The light curve appears to have flattened about 30 d after *B* maximum in all the passbands. Using a smooth cubic spline interpolation between the data points, the peak brightness and its time of occurrence are estimated for all the passbands the values thus obtained are tabulated in Table 2. These values are consistent with, but more accurate than those presented by Gal-Yam et al. (2002b).

The general nature of the light curve of SN 2002ap is similar to that of SN 1998bw (Galama et al. 1998). The light curve of SN 2002ap and its characteristics such as the time of maxima, peak width and the decline slopes are compared with those of the hypernova SN 1998bw and the normal type Ic supernova SN 1994I (Richmond et al. 1996). The values of these parameters are listed in Table 2. In all cases, the flux peaks first at shorter wavelengths and then moves progressively towards longer wavelengths as expected in energetic explosions such as supernovae. The time differences between the maxima at *B* and I_c filters are about 5.5, 3.5 and 3.2 d for SN 2002ap, SN 1998bw and SN 1994I respectively. We define the peak width $\Delta d_{0.25}$ as the width of the light curve at a level 0.25 magnitude below the maximum. The value of $\Delta d_{0.25}$ therefore can be considered as a representative of rise time in the light curve. From Table 2, it can be seen that the peak width ($\Delta d_{0.25}$) of SN 2002ap is smaller than that of SN 1998bw but larger than that of SN 1994I. The $\Delta d_{0.25}$ value is larger at longer wavelengths for all the three SNe and decreases gradually towards the shorter wavelengths. As the absolute magnitude at the time of peak brightness of SN 2002ap is fainter than that of SN 1998bw and SN 1994I, the amount of radio active matter ejected in the SN 2002ap explosion is probably smaller than those in SN 1998bw and SN 1994I.

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Table 2. A comparison of the light curve characteristic parameters of SN 2002ap, SN 1998bw and SN 1994I. Peak JD dates denotes the time of maximum brightness in different filters. $\Delta d_{0.25}$ is defined as the width of light curve (in days) at a level of 0.25 magnitude below maximum. Δm_{15} is defined as decline in magnitude in 15 d after maximum. α_1 and α_2 are the flux decline slopes in mag d^{-1} before and after the flattening respectively. For comparison we have used data points from Galama et al. (1998), McKenzie & Schaefer (1999) and Sollerman et al. (2000) for SN 1998bw and from Richmond et al. (1996) for SN 1994I.

Object	Parameters	U	B	V	R_c	I_c
SN 2002ap	Peak JD date from 2452300+	09.77 ± 0.26	11.49 ± 0.25	13.91 ± 0.37	15.90 ± 0.22	17.24 ± 0.53
	App. Magnitude	13.26 ± 0.02	13.12 ± 0.01	12.38 ± 0.01	12.28 ± 0.01	12.22 ± 0.03
	Absolute Magnitude	−16.48 ± 0.02	−16.57 ± 0.01	−17.22 ± 0.01	−17.25 ± 0.01	−17.23 ± 0.03
	Adopted Extinction	0.427	0.369	0.279	0.209	0.135
	Δm_{15}	–	0.99	0.87	0.73	0.47
	$\Delta d_{0.25}$	5.2	7.9	10.6	13	15.3
	α_1	0.127 ± 0.005	0.082 ± 0.001	0.074 ± 0.001	0.062 ± 0.001	0.040 ± 0.001
	α_2	–	0.0163 ± 0.0001	0.0206 ± 0.0002	0.0177 ± 0.0004	0.0207 ± 0.0002
SN 1998bw	Peak JD date from 2450940+	2.9 ± 0.2	3.8 ± 0.2	5.7 ± 0.2	6.7 ± 0.2	7.3 ± 0.3
	Absolute Magnitude	−19.16 ± 0.10	−18.88 ± 0.05	−19.35 ± 0.05	−19.36 ± 0.05	−19.27 ± 0.05
	Δm_{15}	–	0.56	0.41	0.25	0.18
	$\Delta d_{0.25}$	8.9	11.3	13.3	14.4	18.0
	α_1	0.106 ± 0.007	0.077 ± 0.003	0.061 ± 0.001	0.050 ± 0.001	0.042 ± 0.002
	α_2	–	0.015 ± 0.001	0.019 ± 0.001	0.020 ± 0.001	0.018 ± 0.001
SN 1994I	Peak JD date from 2449400+	49.5 ± 0.1	50.02 ± 0.25	51.86 ± 0.09	52.54 ± 0.11	53.24 ± 0.12
	Absolute Magnitude	−17.99 ± 0.84	−17.68 ± 0.73	−18.09 ± 0.58	−17.99 ± 0.48	−17.78 ± 0.38
	Δm_{15}	–	2.07	1.74	1.46	1.08
	$\Delta d_{0.25}$	–	6.8	7.3	8.3	8.8
	α_1	–	0.125 ± 0.011	0.122 ± 0.002	0.107 ± 0.002	0.084 ± 0.002
	α_2	–	0.021 ± 0.003	0.024 ± 0.001	0.021 ± 0.001	0.023 ± 0.001

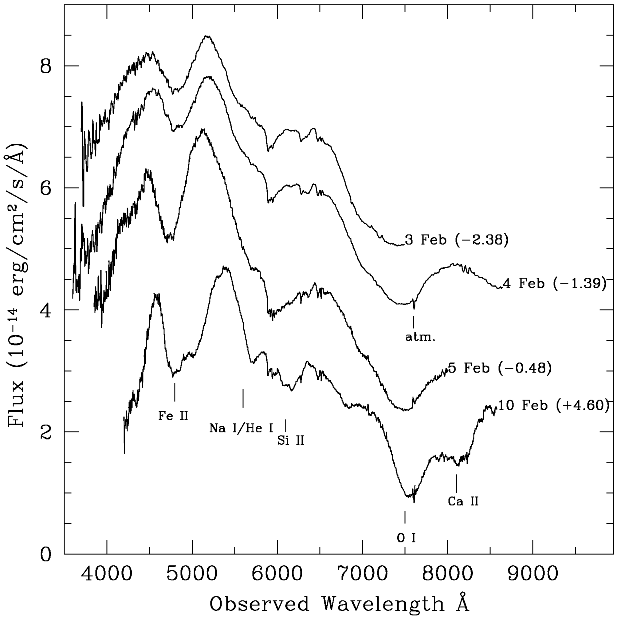

Figure 1. Optical spectra of SN2002ap. The dates of observations along with the days relative to B maximum are indicated. In order to avoid overlap, an offsets of 4.5, 3.5 and 1.7 in flux units, has been added to the spectra of February 3.61, 4.60 and 5.60 respectively.

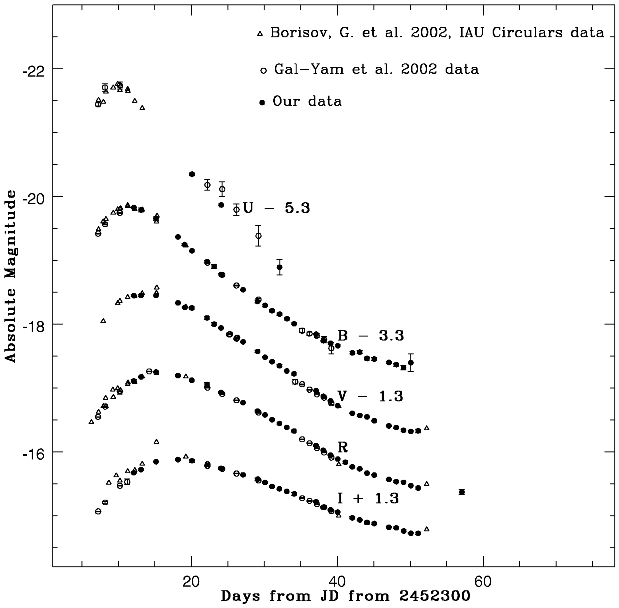

Figure 2. $UBVR_cI_c$ light curve of SN 2002ap. The light curves are offset by a constant value on the magnitude scale as indicated in the plot.

The value of $\Delta d_{0.25}$ peaks in different bands depends on the total ejected mass and the explosion energy (Iwamoto et al. 1998, 2000). The smaller value of $\Delta d_{0.25}$ as seen in the case of SN 1994I means that this supernova ejected a relatively lower mass, producing a relatively thin envelope, which allowed the inner core photons to escape more quickly. Ejection of more massive envelopes increases the diffusion time and leads to a broader peak at light maximum. This appears to be true in the case of SN 1997ef and SN 1998bw. We therefore expect the mass ejected in SN 2002ap to be more

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compared to SN 1994I but slightly less compared to SN 1998bw. This is in agreement with the estimate of the ejected mass determined by Mazzali et al. (2002). Following Richmond et al. (1996), we also estimate Δm_{15}, the magnitude of SN 2002ap 15 d after the outburst maximum, and find the values to be intermediate between SN 1998bw and SN1994I (see Table 2). It can be seen from Table 2 that the values of Δm_{15} indicate an anti-correlation between the decline rate and $\Delta d_{0.25}$, in the sense that a larger decline rate corresponds to a shorter rise time.

Fig. 2 indicates a flattening in the slope of the light curve of SN 2002ap after ~ JD 2542340 in all the passbands. A similar flattening has been observed in the light curves of SN 1998bw and SN 1994I also. However the time of occurrence of this flattening, as measured from the B maximum, is different for the three SNe under discussion. It is about 30 d for SN 2002ap, ~35 d for SN 1994I but ~40 d for SN 1998bw. The flux decline rates (α_1) prior to the flattening for SN 2002ap are wavelength dependent, with values ~0.12, 0.08, 0.07, 0.06 and 0.04 mag d^{-1} in U, B, V, R_c and I_c passbands respectively. A similar trend is also found for SN 1998bw and SN 1994I (see Table 2). Thus the early flux decline values are faster at shorter wavelengths, indicative of expansion of the ejecta, cooling photosphere.

5.2 Light curve after flattening

Fig. 3 shows the late time BVR_cI_c light curve from JD 2542340 to JD 2542520, following the occurrence of the flattening. The slopes of the flattened part (α_2) of the light curves are ~0.02 mag d^{-1} in B, V, R_c and I_c bands corresponding to a value of ~35 d for the half life decay time of the radio active nuclei. A similar decline rate was observed in the case of SN 1998bw also (Patat et al. 2001). A comparison of α_1 and α_2 values indicates that the general nature of all the three SNe are similar for the phases under consideration. The Δm_{15} and α_1 values indicate that the early flux decline rate depends upon wavelength, being fastest at shorter wavelengths. On the other hand the values of α_2 appear to be independent of wavelength.

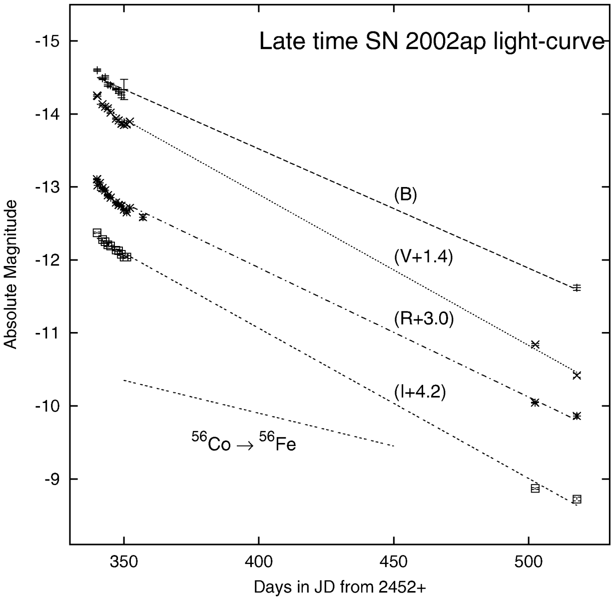

Figure 3. Late time light curve of SN 2002ap. The light curves are offset by a constant value in the magnitude scale, as indicated in the plot. For comparison, slope of the ^{56}Co → ^{56}Fe decay light curve is also shown.

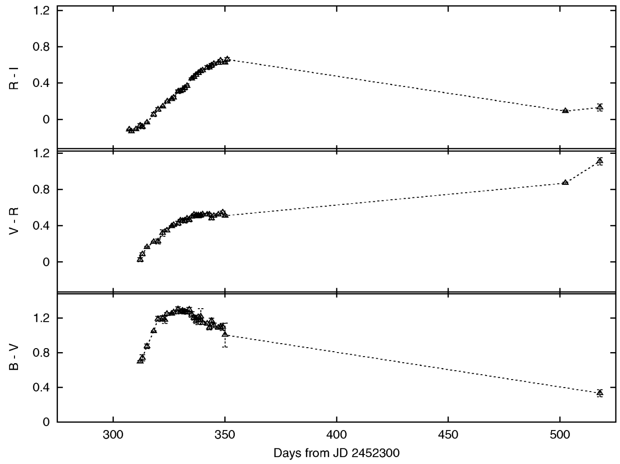

Figure 4. Variation of different colours with time for SN 2002ap.

Further observations are planned for a detailed study of the late-phase light curve development.

6 COLOUR CURVES OF SN 2002AP

The optical colour curves for SN 2002ap are shown in Fig. 4. The earliest measured colours of SN 2002ap are considerably redder than is typical for most supernovae of type Ic. However, they are similar to those of SN 1994I (Richmond et al. 1996). All the colours, $(B-V)$, $(V-R)$ and $(R-I)$, redden from discovery to about JD 2452330. The $(B-V)$ colour then turns blue, until the end of the observations. This turning point most probably occurs when the supernova makes the transition from being optically thick to optically thin. The $(V-R)$ colour on the other hand, continue to redden reaching about 1.1 mag at the end of our observations. The $(R-I)$ colour also shows a trend similar to the $(B-V)$ colour.

The red $(V-R)$, and blue $(R-I)$ colours around 200 d since B maximum can be explained as due to a contribution from strong emission lines to the R band.

7 BOLOMETRIC LIGHT CURVE OF SN 2002AP

Fig. 5 shows the UVOIR bolometric light curve of SN 2002ap, obtained by interpolating and adding contributions from U, B, V, R_c, I_c, J, H and K bands. The magnitudes were converted to flux using calibrations by Fukugita, Shimasaku & Ichikawa (1995) for the U, B, V, R_c and I_c bands and by Bessell & Brett (1988) for the J, H and K bands. The U band contribution has been ignored after JD 2452330, as it falls to negligible values. For the IR bands, we estimate the contribution to the total flux to be ~20 per cent at early epochs (around JD 2452307) and ~ 40 per cent after JD 2452330, as indicated by Mazzali et al. (2002). For a comparison, the slopes of ^{56}Ni → ^{56}Co and ^{56}Co → ^{56}Fe decay curves are also shown in Fig. 5. The bolometric light curve indicates that after reaching a maximum the flux declines exponentially with a decay rate of 0.055 ± 0.001 mag d^{-1}.

Including the late time observations of JD 2452502 and JD 2452517 also, the bolometric light curve indicates a slope of 0.0199 ± 0.0004 mag d^{-1} beyond JD 2452340, assuming a 40 per cent IR contribution to the total bolometric flux for the late time also, as assumed by Mazzali et al. (2002) for the early time. The late time decline is steeper than that expected from ^{56}Co → ^{56}Fe

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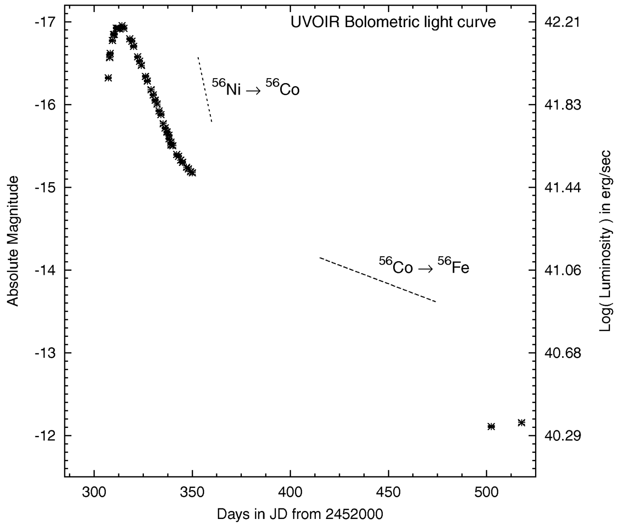

Figure 5. UVOIR bolometric light curve of SN 2002ap. For a comparison, the decay slopes of ^{56}Ni → ^{56}Co and ^{56}Co → ^{56}Fe are also shown.

decay rate, indicating a leakage of γ-rays from the SN envelope (Sollerman, Leibundgut & Spyromilio 1998; Patat et al. 2001).

7.1 ^{56}Ni mass ejected

The amount of ^{56}Ni mass ejected can be estimated using the peak luminosity (Arnett 1982). Using the peak luminosity of $\sim 1.6 \times 10^{42}$ erg s^{-1}, we estimate the amount of ^{56}Ni ejected to be $\sim 0.06\,\mathrm{M}_{\odot}$. This value is consistent with an estimate of $0.07 \pm 0.02\,\mathrm{M}_{\odot}$, obtained by Mazzali et al. (2002) using hydrodynamic model fits to the light curves.

8 CONCLUSIONS

We present dense temporal optical photometric data of SN 2002ap during 2002 February 6 to March 23. $UBVR_cI_c$ photometric light curves of SN 2002ap have been studied by combining our data with those published by others. The broad-band photometric observations taken up to about 40 d after the peak brightness in B indicate that the flux undergoes an exponential decline similar to that observed in other SN Ic. We are the first to report a flattening in the optical light curves at JD 2452340, about 30 d after the B maximum.

The supernova luminosity follows an exponential decline with a relatively faster rate up to JD 2452340. The flux decline rates are 0.127 ± 0.00, 0.082 ± 0.001, 0.074 ± 0.001, 0.062 ± 0.001 and 0.040 ± 0.001 mag d^{-1} in U, B, V, R_c and I_c filters respectively. This indicates a clear dependence of flux decline rate on wavelength, being faster at shorter wavelengths. On the other hand the flux decline rates appear to be wavelength independent after flattening with a value of about 0.02 mag d^{-1}. The photospheric velocities determined by us are ~21 360 and ~10 740 km s^{-1} about −2.38 d before and +4.60 d after the B maxima.

We present the bolometric light curve which illustrates the decay of total luminosity of the supernova. The peak luminosity estimated yields the value of ^{56}Ni mass ejected to be $0.06\,\mathrm{M}_{\odot}$. The measured early decline rate of the bolometric light curve is slower than that expected from ^{56}Ni → ^{56}Co decay, but not inconsistent with that expected from a mixture of iron-peaked nuclei (Colgate & McKee 1969). However as seen from the synthetic light curve in Mazzali et al. (2002), this could also represent an optical depth effect. Late time bolometric light curve decline, steeper than that of ^{56}Co → ^{56}Fe decay may be due to γ-rays leakage from the SN envelope.

We intend to monitor SN 2002ap further, in order to study the nature of its flux decline at late phases.

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