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Supernova 2002ap: the first month

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ABSTRACT

Supernova (SN) 2002ap in M74 was discovered on 2002 January 29. Being one of the nearest (10 Mpc) SN events in the last decades, and spectroscopically similar to the so-called 'hypernovae' 1997ef and 1998bw, both possibly associated with gamma-ray bursts (GRBs), it is of great interest. Shortly after its discovery, we launched an intensive photometric and spectroscopic monitoring campaign of this event, and here we report the results of the first month of observations. We use our *UBVRI* photometry to estimate the magnitudes at, and dates of, peak brightness. Our data suggest that this object reached its peak *B*-band luminosity on February $7.1^{+2}_{-1.3}$ UT. Based on its similarity to SN 1998bw, we estimate the range of possible dates for a GRB that may have been associated with SN 2002ap. We find that it may include dates outside the time frame for which all available gamma-ray data have been intensively scanned, according to recent reports. The absolute magnitude at peak brightness of SN 2002ap ($M_B = -16.9$) shows that it was significantly fainter than SN 1998bw, or normal Type Ia SNe, but similar to SN 1997ef. Our spectroscopic observations confirm that SN 2002ap is strikingly similar to SNe 1998bw and 1997ef. We briefly describe the spectral evolution of this object. To assist other observers and to stimulate theoretical models, we make our entire data set publicly available in digital form (http://wise-obs.tau.ac.il/~avishay/local.html).

Key words: supernovae: individual: SN 2002ap – gamma-rays: bursts.

1 INTRODUCTION

Supernova (SN) 2002ap in M74 was discovered by Y. Hirose and confirmed by R. Kushida and W. Li in images obtained on 2002 January 29 and 30 (Nakano et al. 2002; UT dates are used throughout this Letter). The relative proximity of this event ($v_r = 657\,\mathrm{km\,s^{-1}}$, $D \sim 10\,\mathrm{Mpc}$, Tully 1988) and its ensuing brightness made it a promising target for intensive follow-up studies. Three independent teams promptly obtained low-resolution spectroscopic observations on January 30 (Meikle et al. 2002), and January 31 (Kinugasa et al. 2002; Gal-Yam & Shemmer 2002). All groups noted the spectral resemblance of this object to the so-called 'hypernovae' 1998bw and 1997ef, both of which may have been associated with gamma-ray bursts (GRBs; Galama et al. 1998; Iwamoto et al. 2000). Using the well-sampled spectral observations of SN 1998bw by Patat et al. (2001), Gal-Yam & Shemmer estimated that SN 2002ap was discovered prior to peak brightness. Being both nearby, of a rare type, and possibly connected to GRBs, SN 2002ap became a focus of a multi-wavelength observational effort. Follow up studies include detection in the radio (Berger, Kulkarni & Frail 2002), IR imaging (e.g. Mattila & Meikle 2002) and spectroscopy (e.g., Motohara et al. 2002), UV and X-ray imaging (Rodriguez-Pascual et al. 2002), optical polarimetry (e.g., Wang et al. 2002) and high-resolution spectroscopy (e.g., Lauroesch et al. 2002).

We have undertaken an intensive observational monitoring campaign of this SN with multicolour imaging and low-resolution optical spectroscopy. The backbone of our program consists of target-of-opportunity observations obtained with the Wise Observatory 1-m telescope as part of the queue program. The resulting set of observations presents a coherent picture of the evolution of SN 2002ap in the optical band during the first month since its discovery. As this SN now approaches solar conjunction and will not be observable during the next few months, we have analysed the data set collected so far. In this Letter we briefly report and discuss our main results. All the data presented here are available electronically via our website.[1]

2 OBSERVATIONS

2.1 Photometry

UBVRI photometry was obtained with the Wise Observatory 1-m telescope during nine nights, using the Tektronics (1024 × 1024 pixel) and SITe (2048 × 4096 pixel) CCD cameras. Time

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[1] http://wise-obs.tau.ac.il/~avishay/local.html

Table 1. Local calibrators in the field of SN 2002ap.

#	RA	Dec.	*U*	*B*	*V*	*R*	*I*
1	01:36:19.53	15:45:21.8	14.10	13.84	13.06	12.61	12.14
2	01:36:14.61	15:44:58.2	14.40	14.33	13.69	13.32	12.95
3	01:36:14.32	15:47:01.5	14.30	14.01	13.22	12.77	12.34
4	01:36:14.09	15:47:23.7	15.30	15.10	14.37	14.37	13.56
5	01:36:14.90	15:47:19.4	15.69	15.22	14.38	13.89	13.45
6	01:36:14.56	15:43:38.9	15.32	14.83	13.90	13.40	12.92
7	01:36:32.05	15:45:07.8	15.27	14.11	12.85	12.07	11.35
8	01:36:27.38	15:46:30.3	14.73	14.53	13.80	13.37	12.97
9	01:36:23.04	15:47:45.5	15.17	15.18	14.61	14.26	13.90
10	01:36:04.48	15:43:17.7	13.82	13.61	12.91	12.52	12.16

Notes:
Astrometric solution based on 33 USNO-A2.0 (Monet et al. 1996) stars with final rms scatter of 0.331 and 0.462 arcsec in RA (J2000) and Dec., respectively; Photometric *UBVRI* data are from Henden (2002); Star #8 is the spectroscopic comparison star.

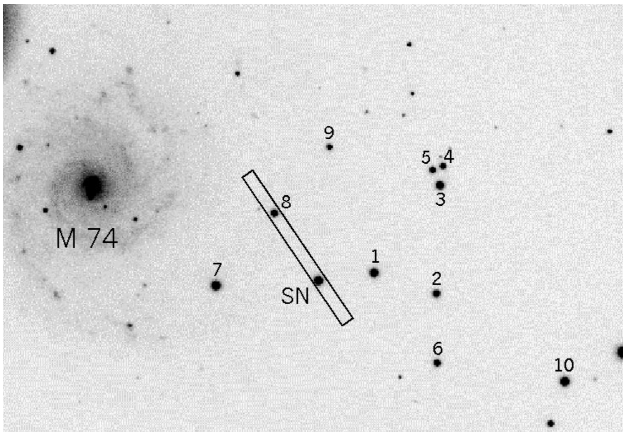

Figure 1. A 12 by 8.3 arcmin section of a combined *BVR* image of the field of SN 2002ap, obtained at the Wise Observatory. Nearby reference stars are marked, as well as the schematic location of the spectroscopic comparison star within the slit.

series of 60-s *V*-band images were obtained on five occasions, in order to search for variability on short (<1 h) time-scales. As no such effects were evident, these data were averaged and used to improve the photometric sampling.

Fig. 1 shows a combined *BVR* image of the field of SN 2002ap, produced from the stacked images obtained during February 2002. As the SN is isolated and contamination by underlying galactic light is constrained to lie below $B = 21.6$ mag (Smartt, Ramirez-Ruiz & Vreeswijk 2002), we used aperture photometry on the SN and nearby reference stars (see Fig. 1 and Table 1). The SN flux was measured and compared with that of nearby bright stars using standard IRAF[2] routines. The photometric stability of each reference star in each band was checked against the entire reference set, and stars with the lowest root-mean-square scatter values were used in the final calibration. 1σ error estimates, including Poisson noise in the SN flux and the scatter in the flux of reference stars, were computed, and found to be below 0.025 mag, except for the *U*-band data, where some points have errors as large as 0.16 mag. In Fig. 2 we plot the resulting *UBVRI* light curves of this object. The data provided by Henden (2002) were used for absolute calibration. We estimate the errors in the absolute zero-point determination to be smaller than 2 per cent. As a consistency check, we compare our photometry with the measurements of Riffeser, Goessl & Ries (2002), and find excellent agreement. We therefore combine their early *UBR* points with our data set. As both our own observations and those of SN 1998bw around peak brightness (Galama et al. 1998) suggest that these objects have smoothly varying light curves, we use cubic spline interpolation to get approximate *UBVRI* curves. From these, we determine the dates of peak brightness, and the SN magnitudes at peak in each band. Conservative margins on the peak dates are set by the latest point seen to be rising and the first to be declining. Assuming that the light curves of SN 2002ap had similar shapes around peak to those of SN 1998bw, we can better constrain the dates of peak by checking by how much one can adjust the peak dates without creating pronounced 'wiggles' or 'humps', not seen in the light curves of Galama et al. (1998) or in well-sampled parts of our own data. The calculated peak dates and their estimated errors, as well as the more conservative margins discussed above, are reported in Table 2, along with the SN absolute magnitudes, calculated assuming the distance modulus to M74 given by Tully (1988), $\mu = 30.24$ for $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. We correct for foreground Galactic extinction according to Schlegel, Finkbeiner & Davis (1998), using the extinction curve of Cardelli, Clayton & Mathis (1989). Based on high-resolution spectroscopic observations, Klose, Guenther & Woitas (2002) estimate that this SN suffered little intrinsic extinction ($A_V \sim 0.025$ mag) in its host, so the absolute magnitudes we derive are probably a fair estimate of the SN luminosity. If so, it is clearly evident that unlike SN 1998bw, SN 2002ap was not optically luminous, being ~ 2 magnitudes fainter in the *B* band. The peak luminosity of SN 2002ap may be comparable to that of SN 1998bw only if the distance to M74 is significantly underestimated. Apart from the lower peak magnitudes, the general shape of the light curves is similar to those of SN 1998bw (Galama et al. 1998). As can be seen in Fig. 2 and Table 2, the light curves are wider in the redder bands, and the bluer the band, the earlier the date of the peak. The decline rates are also similar, with the SN becoming fainter by ~ 1.3 mag in the *V* band some 20 days after peak.

2.2 Spectroscopy

Long-slit spectra of SN 2002ap were obtained with the Wise Observatory 1-m telescope on five nights: 2002 January 31 and

[2] IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

February 7, 14, 21 and 27, using the Faint Object Spectrograph and Camera (FOSC; Brosch & Goldberg 1994). We used a 10-arcsec wide slit, and a 600 line mm^{-1} grism, resulting in a dispersion of 3.75 Å pixel^{-1} ($\sim$8 Å resolution) and a spectral range of $\sim$4000–7800 Å. Two exposures were obtained each night and used to reject cosmic ray hits. Reduction of the bias-subtracted and flat-field corrected spectra was carried out in the usual manner using IRAF. A He–Ar arc spectrum was used for the wavelength solution. In all but the first spectrum, the SN and a nearby bright star were observed simultaneously through the slit (see Fig. 1), providing an intrinsic relative calibration during non-photometric conditions (see, e.g., Kaspi et al. 2000). Our photometry shows this star to be constant (to within photometric errors) during the period of the observations. The wide (10 arcsec) slit ensured that the effects of atmospheric refraction at the non-parallactic angle were not important. Each spectrum of the SN was divided by the simultaneously observed spectrum of the comparison star. A spectrum of the comparison star obtained on February 7, under photometric conditions, was flux calibrated using the Wise Observatory standard sensitivity function and extinction curve. These do not change appreciably from night to night, and are routinely updated using spectrophotometric standard stars. The SN spectra were calibrated to an absolute flux scale by multiplying each SN/star ratio by the flux calibrated spectrum of the comparison star. The January 31 spectrum (taken without the comparison star in the slit) was directly calibrated using the mean curves. The final fluxed spectra were then compared to our photometry (Fig. 2), showing excellent consistency. We estimate that the relative flux calibration of the last four spectra is good to 2–3 per cent, and the absolute flux calibration has an uncertainty of $\sim$10 per cent, at most.

Fig. 3 shows our entire spectroscopic data set. The first spectrum is very blue and almost featureless, peaking around 5000 Å with secondary broad emission peaks around 4200 Å and 6200 Å. This spectral shape closely resembles early time spectra of SN 1997ef (e.g. Garnavich et al. 1997) and 1998bw (e.g., Patat et al. 2001, see also Fig. 4, top panel) leading to the prompt spectral identification of this object (Section 1). Fig. 4 demonstrates that this spectral resemblance continues throughout the epoch of peak brightness

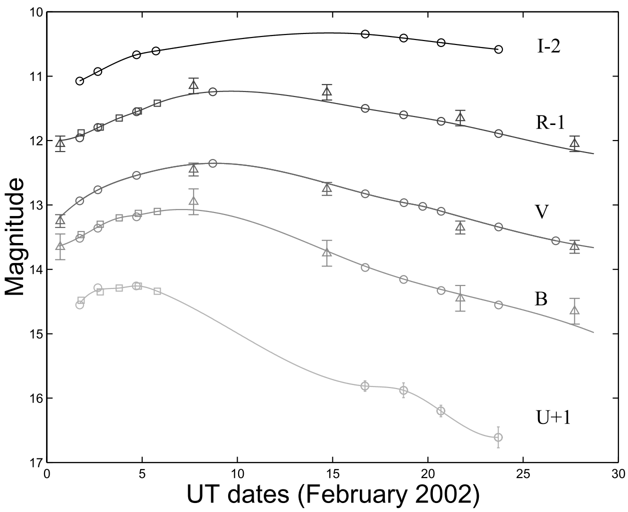

Figure 2. Multicolour light curves of SN 2002ap. Note the excellent agreement between the Wise photometry (circles) and the photometry of Riffeser et al. (2002; squares). For all the points lacking error bars, the estimated errors are smaller than the size of the mark. Photometric points calculated synthetically from Wise spectroscopy (see Poznanski et al. 2002 for details) are marked with triangles. Error bars reflect the combined uncertainties resulting from the flux calibration of the spectra and, in some cases, incomplete spectral coverage of the filter bandpasses. The solid lines are cubic-spline interpolations between the photometric points. For clarity, the *U*, *R* and *I* light curves have been shifted by the amounts noted on the plot.

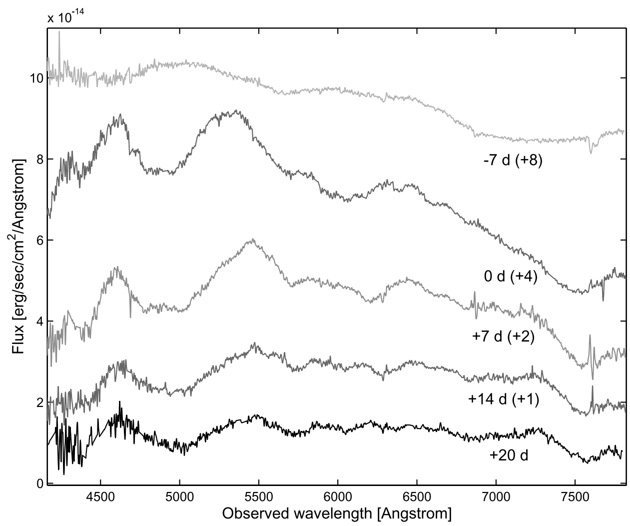

Figure 3. Time sequence of Wise Observatory spectra of SN 2002ap. For each spectrum we note the SN age relative to our best estimate *B*-band maximum, February 7.1. For clarity, some of the spectra were vertically shifted by the amounts noted in parenthesis, in units of 10^{-14} erg s^{-1} cm^{-2} Å^{-1}. We have replaced short regions in the spectra, strongly affected by cosmic-ray hits, with linear interpolations. Features around 6300, 6900 and 7600Å, are residuals from imperfectly removed sky lines and telluric absorption.

Table 2. SN 2002ap peak dates and magnitudes.

	U	*B*	*V*	*R*	*I*
Peak date (2002 February)	4.7^{+1}_{-1}	$7.1^{+2}_{-1.3}$	8.8^{+2}_{-2}	9.7^{+2}_{-2}	14.8^{+1}_{-4}
Possible range (days)	$^{+1.1}_{-1.9}$	$^{+7.6}_{-1.3}$	$^{+5.9}_{-4}$	$^{+7.9}_{-3.9}$	$^{+3.9}_{-9}$
Apparent magnitude	13.3	13.1	12.4	12.2	12.3
Absolute magnitude	−16.6	−16.9	−17.7	−17.8	−17.8
Adopted extinction	0.387	0.307	0.236	0.190	0.138

Note:
The given peak dates were estimated from cubic spline interpolations and their errors estimated assuming that the light curves of SN 2002ap were similar to those of SN 1998bw around peak (see text). The most conservative range of possible dates for the peak in each band was set to lie between the latest point seen to be rising and the earliest seen to be on the decline.

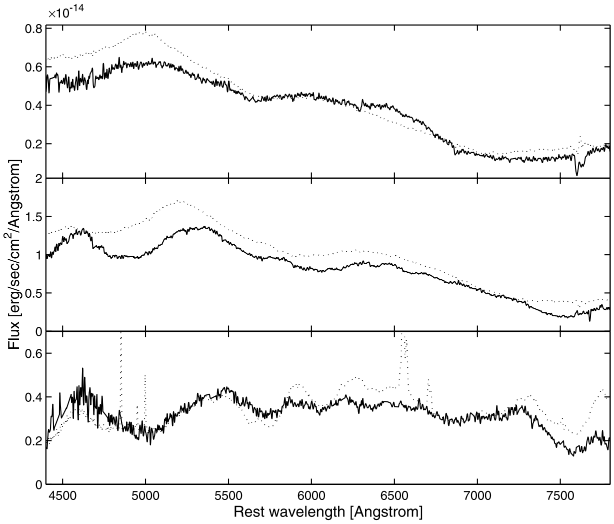

Figure 4. Comparison of Wise spectra of SN 2002ap (solid lines) with contemporary spectra of SN 1998bw (dotted line) at ages 7 days before peak (top panel) and at peak magnitude (middle panel), from Patat et al. (2001). The bottom panel demonstrates the resemblance of the spectrum of SN 2002ap at age 20 d (solid line) to SN 1997ef at age 40 d (dotted line; from Matheson et al. (2001); the superposed narrow lines are from the underlying galaxy; earlier spectra of SN 1997ef were not available in digital form).

(unless otherwise noted, from here on we refer to our best estimate *B*-band peak date, February 7.1 UT, as the time of peak brightness), and up until the date of our last spectrum (∼20 days after maximum).

The spectral evolution of SN 2002ap displays several characteristic trends also identified in 1997ef (Matheson et al. 2001, Iwamoto et al. 2000) and 1998bw (Stathakis et al. 2000, Patat et al. 2001, and references therein). These include the reddening of the continuum, a redward shift and narrowing of prominent 'emission-like' and 'absorption-like'[3] features, and decreasing values of the expansion velocities. Following Patat et al. (2001) we have calculated expansion velocities from the Si II λ6355 absorption, and find a decrease from $\sim 38\,000\,\mathrm{km\,s^{-1}}$ 7 days prior to peak to $\sim 15\,000\,\mathrm{km\,s^{-1}}$ at peak, and to $\sim 6000\,\mathrm{km\,s^{-1}}$ 14 days later. This is similar to the results obtained for 1998bw, and consistent with the measurements of Motohara et al. (2002; $\sim 16\,000\,\mathrm{km\,s^{-1}}$ around peak from 1.083 μm He I) and Filippenko & Chornock (2002; $\sim 9000\,\mathrm{km\,s^{-1}}$ four days after peak from 7774 Å O I). The prominence of the 4600 Å emission peak relative to the one bluewards of 5000 Å (both tentatively attributed to Fe II blends, e.g., Patat et al. 2001 and references therein) in spectra of SN 2002ap at and after peak resembles spectra of SN 1997ef but differs somewhat from those of SN 1998bw. A notable feature in the spectra of SN 2002ap is a narrow, unresolved absorption, consistent with He II λ4686. This feature first emerges in the spectrum taken near peak brightness and is stronger still seven days later. It does not appear in later spectra of the object, nor in spectra of either SN 1997ef or 1998bw.

[3] Model synthetic spectra show that at early times, the spectral shape of these objects is determined by the wavelength dependence of the absorption optical depth, so that features in the spectrum cannot generally be attributed to a certain emission or absorption line (e.g. Patat et al. 2001, and references within).

3 DISCUSSION AND CONCLUSIONS

We have presented the results of our optical photometric and spectroscopic monitoring of SN 2002ap, during the first month after its discovery. Our best estimate for the date of *B*-band maximum is 2002 February 7.1, and our derived peak magnitude of $M_B = -16.9$ is significantly lower than the one measured for the 'hypernova' SN 1998bw. However, except for the lower peak magnitude, the characteristics of the light curves, as well as the spectral evolution of this object, are strikingly similar to those of SNe 1997ef and 1998bw. Our work shows that, at least to some degree, one may use the well studied properties of SN 1998bw as a tentative basis upon which to plan future observations of SN 2002ap, after scaling the peak magnitude.

In light of its similarity to SNe 1998bw and 1997ef, one of the intriguing questions about SN 2002ap is whether it was also associated with a GRB. Using our most conservative estimate for the date of the *B*-band peak, February $7.1^{+7.6}_{-1.3}$ d (Table 2), and assuming that the lag between a hypothetical GRB and the time of *B*-band maximum is similar to that measured for SN 1998bw (14.3 d, Galama et al. 1998), we would expect the GRB trigger to have occurred around January $23.8^{+7.6}_{-1.3}$ d. However, if we use instead our estimated *U*-band peak date, February $4.7^{+1.1}_{-1.9}$ d, which is best constrained by our photometry, along with the appropriate *U*-band time lag from Galama et al. 1998 (13.7 d), the resulting GRB trigger time is January $22.0^{+1.1}_{-1.9}$ d. Hurley et al. (2002) found no candidate GRB that might be associated with SN 2002ap in an intensive search of gamma-ray data from all available sources, starting January 21. Our results suggest that the GRB trigger may have occurred outside the time frame searched. If the GRB-peak magnitude time lag for SN 2002ap was just one day longer than the lag measured for SN 1998bw, the trigger is likely to have been missed by Hurley et al. We conclude that in order to detect, or set a secure upper limit to the fluence of a GRB associated with SN 2002ap, a search similar to the one reported by Hurley et al. should be extended to include data taken several days prior to January 21.

Finally, there remains the question of the classification of SN 2002ap and its look-alikes, SNe 1998bw and 1997ef (and possibly also SN 1998ey, Garnavich, Jha & Kirshner 1998, and the recent SN 2002bl, Filippenko, Leonard & Moran 2002). Various authors have used various types for these events, usually some combination of Ib, Ic and 'peculiar'. In view of the fact that these SNe are spectroscopically similar to each other, but well distinguished from prototypical SNe Ib (e.g. SN 1984L) or Ic (e.g., SN 1987M or 1994I), we suggest that they be defined as a new SN sub-type, and provisionally designate them as Type Id SNe. This should replace the often used nickname 'hypernovae', initially used to describe the unusually energetic and luminous SN 1998bw (Iwamoto et al. 1998). This term has since become somewhat misleading as it was later applied to events that were modelled as highly energetic explosions, but were not especially luminous, such as SN 1997ef (Iwamoto et al. 2000). Currently, all events that are spectroscopically similar to SNe 1998bw and 1997ef, e.g., 2002ap and 2002bl, are sometimes referred to as 'hypernovae' for lack of a better name, even though they are not known to be very luminous or exceptionally energetic. Admittedly, these events are probably closer to Type Ic SNe than to any other sub-type, and the physical differences between them and other Type Ic's are not fully understood. However, the current SN classification scheme is purely observational and based mostly on optical spectroscopic properties (see Filippenko 1997, for a review). In our opinion, the difference between the early-time spectra of the three well-studied

'Id' events and those of prototypical Ib and Ic SNe are no less significant than the differences between other types of SNe. So much so that there was some question as to whether the first of these events, 1997ef, was in fact a SN, when judged by its earliest spectra (Garnavich et al. 1997).

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NOTE ADDED IN PROOF

A recent preprint by Mazzali et al. (2002) reports an independent set of photometric and spectroscopic observations that are fully consistent with those presented here.

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