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The Type IIb SN 2008ax: spectral and light curve evolution

A. Pastorello,[1★] M. M. Kasliwal,[2,†] R. M. Crockett,[1] S. Valenti,[1] R. Arbour,[3] K. Itagaki,[4] S. Kaspi,[5,6] A. Gal-Yam,[7] S. J. Smartt,[1] R. Griffith,[8,9] K. Maguire,[1] E. O. Ofek,[2] N. Seymour,[10] D. Stern[9] and W. Wiethoff[11]

[1] *Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN*
[2] *Division of Physics, Mathematics, and Astronomy, 105-24, California Institute of Technology, Pasadena, CA 91125, USA*
[3] *Pennell Observatory, 29 Wrights Way, South Wonston, Hants SO21 3HE*
[4] *Itagaki Astronomical Observatory, Teppo-cho, Yamagata 990-2492, Japan*
[5] *School of Physics and Astronomy and the Wise Observatory, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel*
[6] *Physics Department, Technion, Haifa 32000, Israel*
[7] *Benoziyo Center for Astrophysics, Weizmann Institute of Science, 76100 Rehovot, Israel*
[8] *Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA*
[9] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*
[10] *Spitzer Science Center, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA*
[11] *Port Wing, WI 54865, USA*

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ABSTRACT

We present spectroscopy and photometry of the He-rich supernova (SN) 2008ax. The early-time spectra show prominent P-Cygni H lines, which decrease with time and disappear completely about 2 months after the explosion. In the same period He I lines become the most prominent spectral features. SN 2008ax displays the ordinary spectral evolution of a Type IIb supernova. A stringent pre-discovery limit constrains the time of the shock breakout of SN 2008ax to within only a few hours. Its light curve, which peaks in the *B* band about 20 d after the explosion, strongly resembles that of other He-rich core-collapse supernovae. The observed evolution of SN 2008ax is consistent with the explosion of a young Wolf–Rayet (of WNL type) star, which had retained a thin, low-mass shell of its original H envelope. The overall characteristics of SN 2008ax are reminiscent of those of SN 1993J, except for a likely smaller H mass. This may account for the findings that the progenitor of SN 2008ax was a WNL star and not a K supergiant as in the case of SN 1993J, that a prominent early-time peak is missing in the light curve of SN 2008ax, and that Hα is observed at higher velocities in SN 2008ax than in SN 1993J.

Key words: supernovae: general – supernovae: individual: SN 2008ax – supernovae: individual: SN 1993J – galaxies: individual: NGC 4490.

1 INTRODUCTION

In recent years, the attention of the astronomical community towards H-poor core-collapse (CC) supernovae (SNe) has significantly increased. This is due to the discovery, during the late 1990s, of the connection between H- and He-stripped CC SNe (of Type Ic) and long duration gamma-ray bursts (GRBs, see e.g. Galama et al. 1998; Woosley & Bloom 2006). However, interest in He-rich events (Type Ib) has been rather marginal so far, although recently invigorated by the discovery of early X-ray emission from the Type Ib SN 2008D (SN 2008D, Malesani et al. 2008; Soderberg et al. 2008). Equally poorly studied are the very few SN events in which there is spectroscopic evidence for the presence of H lines in otherwise normal Type Ib SN spectra. These rare CC SNe were dubbed as Type IIb by Woosley et al. (1987) (see also Filippenko 1997), and their hybrid spectroscopic appearance was interpreted as the result of the explosion of a He core of an originally massive star, which had retained a residual (though marginal) H envelope (few $\times 10^{-1}$ M$_{\odot}$) at the time of explosion.

The explosion of the very nearby SN 1993J offered the unique opportunity to study in detail the evolution of a Type IIb event and to detect the progenitor star in pre-explosion images (Aldering et al. 1994; Cohen, Darling & Porter 1995; Van Dyk et al. 2002), although it would be more correct to state that the binary system

★E-mail: a.pastorello@qub.ac.uk (AP)
†Hale Fellow, Gordon and Betty Moore Foundation

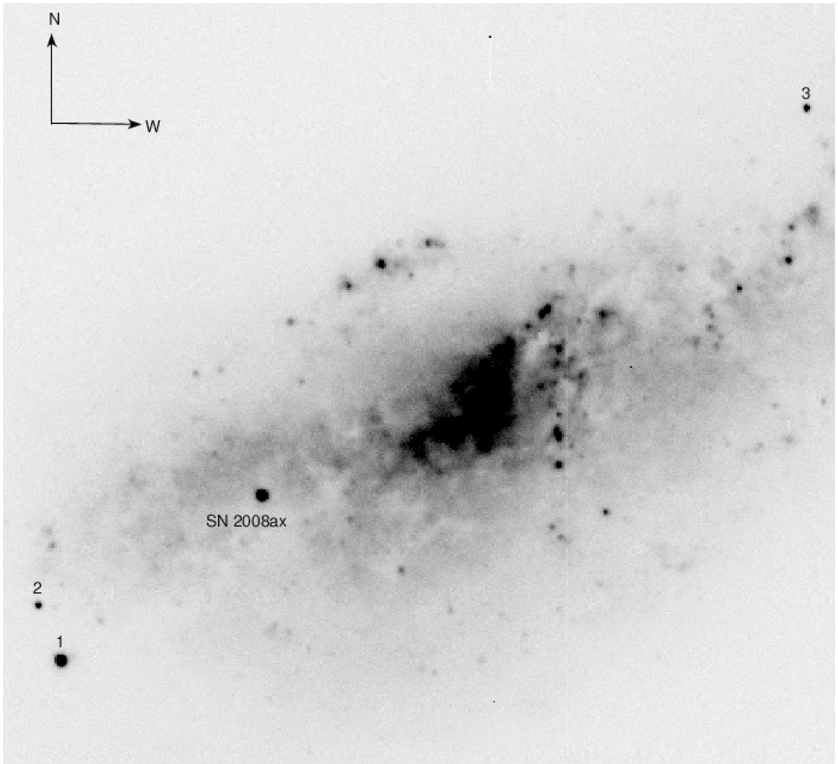

Figure 1. SN 2008ax in NGC 4490. *V*-band image obtained on 2008 March 22, with the Liverpool Telescope (equipped with RatCAM). Three photometric comparison stars are also labelled.

producing SN 1993J was observed in the pre-SN images, since signatures of the presence of a massive, blue companion star arose from spectrophotometric observations of the SN site obtained about 10 yr after the SN explosion (Maund et al. 2004). These exceptional data constrained the precursor of SN 1993J to be a K supergiant of initial mass around 14 $M_{\odot}$, but with a He core of only 3–6 $M_{\odot}$ at the time of the explosion (see also Nomoto et al. 1993; Podsiaklowski et al. 1993; Woosley et al. 1994).

Another Type IIb event, SN 2001ig, showed periodic modulation in its radio light curve. This may indicate either density enhancements indicative of circumstellar shells produced in the thermal-pulsing phase by a single asymptotic giant branch star or, more likely, a stellar wind modulated by motion in an eccentric binary system[1] (Ryder et al. 2004). The binary system scenario is also supported by spectropolarimetric observations of SN 2001ig (Maund et al. 2007). Interestingly, a point-like source was detected at the SN position about 1000 d after the explosion, possibly the massive (10–18 $M_{\odot}$) companion of the Wolf–Rayet (WR) star producing SN 2001ig (Ryder, Murrowood & Stathakis 2006).

Apart from SN 1993J (e.g. Richmond et al. 1994; Lewis et al. 1994; Barbon et al. 1995), extensive data sets have been published for only a very limited number of He-rich CC SNe, including SNe 1987K (Filippenko et al. 1988), 1990I (Elmhamdi et al. 2004), 1996cb (Qiu et al. 1999), 1999dn (Deng et al. 2000, Benetti et al. in preparation), 1999ex (Stritzinger et al. 2002; Hamuy et al. 2002), 2008D (Soderberg et al. 2008), plus the peculiar SNe 1991D (Benetti et al. 2002), 2001gh (Elias-Rosa et al. in preparation) and 2005bf (Anupama et al. 2005; Tominaga et al. 2005; Folatelli et al. 2006). SN 2006jc and similar events (the so-called SNe Ibn, see Pastorello et al. 2008a) are different because the He is mostly confined in the circumstellar environment (Matheson et al. 2000; Foley et al. 2007; Pastorello et al. 2007; Immler et al. 2008; Mattila et al 2008; Pastorello et al. 2008b; Smith, Foley & Filippenko 2008; Tominaga et al. 2008).

SN 2008ax is therefore the second He-rich CC SN that has excellent spectrophotometric monitoring, and for which we can derive directly information on the progenitor, through the analysis of deep pre-explosion archive images (Crockett et al. 2008). In this paper, we present spectroscopy and photometry of SN 2008ax, while in the companion paper (Crockett et al. 2008) we study in detail the nature of the SN precursor.

2 SN 2008AX AND ITS HOST GALAXY

SN 2008ax (see Fig. 1) was discovered independently by Mostardi, Li & Filippenko (2008, on March 3.45 UT) and Nakano & Itagaki (2008, on March 4.62 UT) in the nearby barred spiral galaxy (Type SBcd) NGC 4490. The new object was around 16th magnitude at discovery. The coordinates were $\alpha = 12^{\rm h}30^{\rm m}40\overset{\rm s}{.}80$ and $\delta = +41^{\circ}38'14\overset{''}{.}5$, quite far ($53\overset{''}{.}1$ East and $25\overset{''}{.}8$ South) from the centre of the host galaxy (Mostardi et al. 2008). Remarkably, the explosion site was monitored by Arbour (2008) about 6 h (JD = 245 4528.7) before the detection of Mostardi et al. (2008) (JD 245 4528.95) and the images show no sign of the SN. This allows us to constrain the time of the shock breakout to high precision, with an uncertainty of only a few hours. Hereafter in the paper we will

[1] Soderberg et al. (2006) also explained the observed modulation in the radio light curves of the Type IIb SNe 2001ig and 2003bg in terms of density enhancements due to quasi-periodic mass loss episodes from massive WR progenitors, occurred soon prior to the SN explosions.

Table 1. Optical photometry of SN 2008ax.

Date	JD	u'	B	V	g'	r'	i'	z'	Instrument
Mar 05	245 4530.70				16.756 0.053	15.990 0.039	16.194 0.055	16.127 0.133	P60
Mar 05	245 4530.79				16.802 0.089	16.034 0.076	16.185 0.038	16.093 0.031	P60
Mar 05	245 4530.90				16.765 0.076	16.037 0.055	16.184 0.117		P60
Mar 06	245 4531.58		17.323 0.210	16.290 0.067		15.826 0.056	15.867 0.055		LT
Mar 06	245 4531.70				16.615 0.030	15.792 0.050	15.946 0.085	15.884 0.056	P60
Mar 06	245 4531.79				16.657 0.139	15.781 0.048	15.997 0.126	15.837 0.087	P60
Mar 06	245 4531.87				16.634 0.098	15.806 0.103	15.950 0.065	15.874 0.118	P60
Mar 06	245 4531.96				16.614 0.033	15.785 0.039	16.006 0.105	15.817 0.026	P60
Mar 06	245 4532.04				16.587 0.060				P60
Mar 07	245 4532.55		17.021 0.032	15.952 0.042		15.509 0.024	15.576 0.027		LT
Mar 07	245 4533.03				16.277 0.102	15.395 0.129			P60
Mar 08	245 4533.53	17.794 0.069	16.548 0.029	15.528 0.014		15.233 0.019	15.258 0.017		LT
Mar 08	245 4533.69				15.992 0.072	15.265 0.109	15.377 0.099		P60
Mar 08	245 4533.78				16.004 0.053	15.206 0.085	15.359 0.104	15.190 0.085	P60
Mar 08	245 4533.86				16.012 0.079				P60
Mar 09	245 4534.57	17.226 0.040	16.082 0.017	15.270 0.011		14.974 0.012	15.012 0.011		LT
Mar 10	245 4535.60	16.746 0.035	15.766 0.018	14.983 0.012		14.778 0.012	14.771 0.009		LT
Mar 10	245 4536.49	16.435 0.036	15.545 0.021	14.819 0.013		14.654 0.016	14.624 0.014		LT
Mar 11	245 4536.68				15.236 0.043	14.745 0.227	14.678 0.087	14.451 0.080	P60
Mar 11	245 4537.47	16.002 0.034	15.264 0.014	14.592 0.011		14.416 0.013	14.461 0.013		LT
Mar 12	245 4537.77				14.965 0.084	14.443 0.025	14.451 0.095	14.362 0.131	P60
Mar 13	245 4538.68				14.888 0.059	14.342 0.034	14.344 0.067	14.283 0.124	P60
Mar 14	245 4539.68				14.689 0.053	14.257 0.034	14.186 0.075	14.061 0.085	P60
Mar 14	245 4540.42	15.298 0.028	14.695 0.013	14.133 0.010		14.007 0.012	13.932 0.010		LT
Mar 15	245 4541.43	15.099 0.031	14.538 0.015	14.005 0.010		13.907 0.014	13.856 0.013		LT
Mar 18	245 4543.55	14.759 0.031	14.354 0.016	13.808 0.010		13.710 0.012	13.633 0.011		LT
Mar 18	245 4543.67				14.145 0.181	13.749 0.102	13.641 0.132		P60
Mar 18	245 4544.36	14.700 0.040	14.338 0.014	13.714 0.010		13.677 0.011	13.546 0.010		LT
Mar 19	245 4544.66				14.147 0.050	13.714 0.083	13.564 0.062	13.561 0.052	P60
Mar 20	245 4545.87					13.608 0.061	13.533 0.037	13.537 0.068	P60
Mar 21	245 4546.66							13.449 0.056	P60
Mar 21	245 4547.36	14.669 0.300	14.165 0.020	13.546 0.012		13.448 0.011	13.345 0.010		LT
Mar 24	245 4549.65				13.971 0.050	13.436 0.030	13.366 0.069	13.456 0.338	P60
Mar 25	245 4550.65				14.025 0.122	13.458 0.094	13.315 0.126	13.396 0.228	P60
Mar 26	245 4551.64				13.981 0.019	13.454 0.149	13.322 0.075	13.274 0.046	P60
Mar 27	245 4552.68				14.034 0.038	13.420 0.033	13.259 0.123	13.312 0.238	P60
Mar 28	245 4553.64				14.117 0.049	13.429 0.092	13.287 0.144	13.276 0.095	P60
Mar 28	245 4554.37	15.849 0.029	14.545 0.015	13.657 0.009		13.406 0.011	13.270 0.010		LT
Mar 29	245 4554.66				14.161 0.062	13.471 0.047	13.328 0.098	13.325 0.087	P60
Mar 29	245 4555.47	16.149 0.026							LT
Mar 31	245 4556.56	16.441 0.025	14.877 0.012	13.837 0.009		13.578 0.011	13.371 0.009		LT
Mar 31	245 4556.75				14.391 0.111	13.574 0.056	13.380 0.110		P60
Mar 31	245 4557.37	16.719 0.034	15.060 0.014	13.915 0.010		13.642 0.011	13.398 0.015		LT
Apr 01	245 4557.64				14.515 0.049	13.658 0.118	13.432 0.127	13.383 0.041	P60
Apr 01	245 4558.34	16.892 0.064	15.254 0.021	13.996 0.013		13.680 0.018	13.428 0.018		LT
Apr 02	245 4558.63				14.676 0.097	13.701 0.020	13.528 0.082	13.489 0.115	P60
Apr 03	245 4559.70				14.669 0.049	13.759 0.122	13.482 0.035		P60
Apr 03	245 4560.48	17.325 0.034	15.460 0.014	14.168 0.009		13.821 0.013	13.525 0.018		LT
Apr 04	245 4560.63				14.828 0.074	13.856 0.109	13.566 0.068		P60
Apr 05	245 4561.75	17.518 0.032	15.587 0.013	14.244 0.010		13.902 0.012	13.567 0.011		LT
Apr 05	245 4562.38	17.606 0.069	15.636 0.017	14.346 0.012		13.962 0.012	13.621 0.011		LT
Apr 12	245 4569.37	18.044 0.056	16.066 0.014	14.687 0.012		14.305 0.011	13.895 0.009		LT
Apr 14	245 4571.37	18.078 0.044	16.133 0.017	14.741 0.011		14.401 0.012	13.972 0.010		LT
Apr 15	245 4572.37	18.090 0.089	16.162 0.018	14.796 0.012		14.423 0.014	13.992 0.039		LT
Apr 16	245 4573.38	18.095 0.032	16.177 0.014	14.832 0.011		14.436 0.013	14.012 0.015		LT
Apr 18	245 4575.36	18.099 0.062	16.231 0.021	14.867 0.010		14.482 0.011	14.065 0.010		LT
Apr 19	245 4576.37	18.106 0.041	16.255 0.015	14.903 0.011		14.528 0.013	14.096 0.011		LT
Apr 20	245 4577.40	18.120 0.043	16.288 0.016	14.930 0.010		14.571 0.011	14.124 0.010		LT
Apr 21	245 4578.37	18.126 0.043	16.293 0.019	14.951 0.011		14.586 0.016	14.147 0.013		LT
Apr 22	245 4579.38	18.124 0.038	16.293 0.017	14.961 0.011		14.607 0.011	14.160 0.016		LT
Apr 25	245 4581.50	18.151 0.070							LT
Apr 30	245 4586.68		16.425 0.038	15.114 0.015		14.800 0.014			LT

Table 1 – *continued*

Date	JD	u'	B	V	g'	r'	i'	z'	Instrument
May 06	245 4592.82				15.888 0.037	14.896 0.038	14.548 0.049	14.070 0.056	P60
May 08	245 4594.72				15.910 0.052	14.958 0.045	14.590 0.056	14.094 0.058	P60
May 09	245 4596.37		16.554 0.020	15.324 0.010		15.033 0.012	14.583 0.010		LT
May 10	245 4596.73				15.920 0.034	15.041 0.102	14.627 0.053	14.137 0.041	P60
May 12	245 4599.38	18.149 0.031	16.571 0.017	15.376 0.010		15.100 0.011	14.611 0.012		LT

Note: LT = 2-m Liverpool Telescope + RatCAM; P60 = Robotic Palomar 60-inch Telescope + CCD.

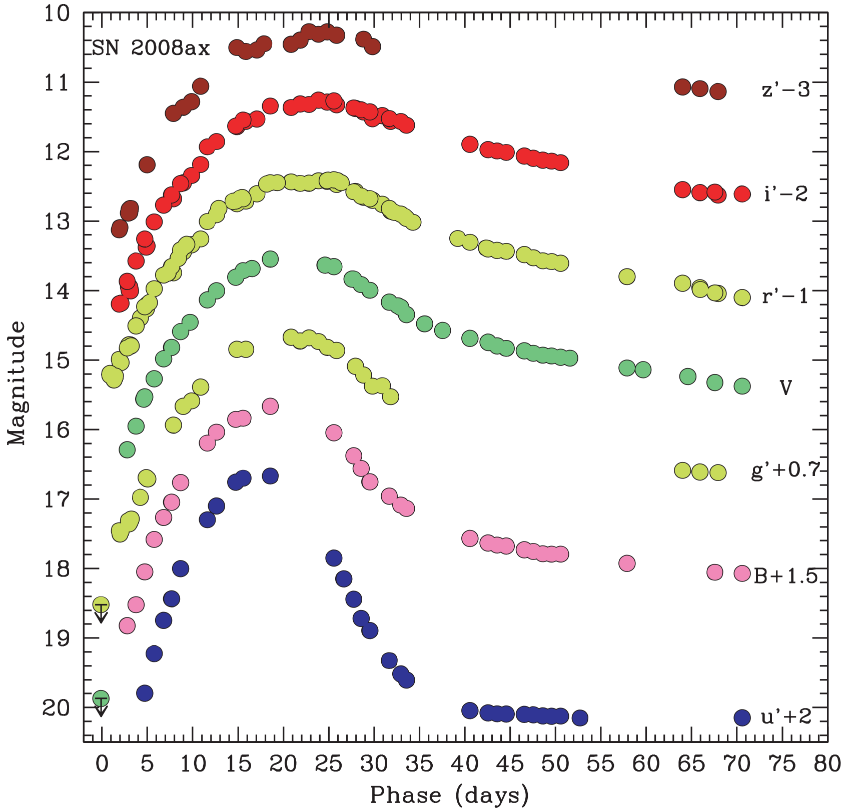

Figure 2. u' BVg' r' i' z' light curves of SN 2008ax until 2 months after the explosion. The phase is computed since shock breakout.

adopt JD = 245 4528.80 ± 0.15 as the time of the shock breakout, and all phases will be computed with reference to this epoch.

NGC 4490 and NGC 4485 are a well-known pair of late-type, interacting galaxies embedded in an extended and asymmetric H I envelope (Huchtmeier, Seiradakis & Materne 1980), which is elongated perpendicularly to the plane of NGC 4490. Clemens, Alexander & Green (1998) claim that the configuration of the neutral hydrogen envelope might result from a bipolar outflow of H I driven by starburst activity/SN explosions, and not from the interaction between the two companion galaxies. This is in agreement with the particularly high star formation rate estimated in NGC 4490 (Viallefond, Allen & de Boer 1980; Thronson et al. 1989; Clemens et al. 1999).

The distance modulus (μ) for NGC 4490 is not well constrained. From Tully (1988) and assuming a Hubble constant $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, we would obtain $\mu = 29.55$ mag. However, Roberts et al. (2002) noted that Tully (1988) gave significantly inconsistent distance estimates for the two interacting galaxies, 9.7 Mpc for NGC 4485 and 8.1 Mpc for NGC 4490 (with our choice of H_0). This inconsistency in Tully's estimate for the two companion galaxies suggests a need to compute the distance to NGC 4490 also using different approaches. An attempt to estimate the distance of the SN host galaxy was performed by Terry, Paturel & Ekholm (2002). It was determined from the technique of sosie galaxies (Paturel et al. 1994) making use of a number of different calibrators for which the distances were computed from two independent Cepheid calibrations. This method gives $\mu = 29.90 \pm 1.16$ mag ($d = 9.5$ Mpc). A further possibility is to derive the distance via the recessional velocity of the SN host galaxy. LEDA[2] (Paturel et al. 2003) provides a recessional velocity for NGC 4490 corrected for Local Group infall into the Virgo Cluster of $v_{\mathrm{Vir}} = 797\,\mathrm{km\,s^{-1}}$. From this, we obtain a distance d of ∼11.1 Mpc, corresponding to a distance modulus $\mu = 30.22$ mag. If we consider the recessional velocity with respect to the cosmic microwave background (CMB) background ($v_{3k} = 817\,\mathrm{km\,s^{-1}}$), we obtain $\mu = 30.27$ mag ($d = 11.3$ Mpc). A lower distance is estimated from the recessional velocity corrected to the centroid of the local group, $v_{\mathrm{lg}} = 618\,\mathrm{km\,s^{-1}}$, which gives $\mu = 29.67$ mag ($d = 8.6$ Mpc). Averaging these five estimates to minimize the uncertainty, we

[2]http://leda.univ-lyon1.fr/

Table 2. Unfiltered photometry of SN 2008ax from amateur astronomers, rescaled to the Johnson–Bessell V and/or Sloan r' bands.

Date	JD	CV	Cr'	Observer
Mar 03	245 4528.70	>19.87	>19.52	RA
Mar 04	245 4529.67		16.210 0.188	WW
Mar 04	245 4529.68		16.220 0.200	WW
Mar 04	245 4529.69		16.192 0.195	WW
Mar 04	245 4530.12		16.272 0.090	KI
Mar 04	245 4530.12		16.285 0.127	KI
Mar 04	245 4530.13		16.282 0.109	KI
Mar 04	245 4530.13		16.277 0.127	KI
Mar 04	245 4530.14		16.271 0.078	KI
Mar 04	245 4530.15		16.264 0.110	KI
Mar 04	245 4530.15		16.259 0.088	KI
Mar 04	245 4530.15		16.261 0.145	KI
Mar 04	245 4530.16		16.255 0.079	KI
Mar 04	245 4530.18		16.252 0.108	KI
Mar 04	245 4530.25		16.249 0.104	KI
Mar 04	245 4530.25		16.239 0.084	KI
Mar 04	245 4530.29		16.229 0.141	KI
Mar 06	245 4532.03		15.795 0.167	KI
Mar 07	245 4533.41	15.562 0.031		RA
Mar 08	245 4534.04		15.172 0.135	KI
Mar 10	245 4536.05		14.751 0.083	KI
Mar 10	245 4536.06		14.747 0.109	KI
Mar 11	245 4537.21		14.536 0.114	KI
Mar 11	245 4537.21		14.535 0.099	KI
Mar 12	245 4538.01		14.356 0.136	KI
Mar 12	245 4538.13		14.334 0.129	KI
Mar 13	245 4538.51	14.457 0.040		RA
Mar 16	245 4541.67		13.818 0.121	WW
Mar 17	245 4543.24		13.718 0.126	KI
Mar 18	245 4544.07		13.669 0.112	KI
Mar 18	245 4544.25		13.660 0.129	KI
Mar 19	245 4545.35	13.683 0.118		RA
Mar 21	245 4546.97		13.468 0.113	KI
Mar 22	245 4548.15		13.448 0.096	KI
Mar 27	245 4553.39	13.634 0.043		RA
Mar 28	245 4553.60		13.420 0.127	WW
Mar 28	245 4553.72		13.413 0.100	WW
Mar 29	245 4554.69		13.415 0.123	WW
Mar 29	245 4555.17		13.448 0.118	KI
Mar 30	245 4556.36	13.836 0.055		RA
Apr 04	245 4560.84		13.863 0.086	WW
Apr 04	245 4561.09		13.877 0.075	KI
Apr 04	245 4561.40	14.219 0.060		RA
Apr 05	245 4562.16		13.935 0.106	KI
Apr 06	245 4563.07		14.017 0.063	KI
Apr 07	245 4564.38	14.479 0.030		RA
Apr 09	245 4566.35	14.575 0.044		RA
Apr 11	245 4568.02		14.251 0.074	KI
Apr 14	245 4571.18		14.387 0.121	KI
Apr 14	245 4571.41	14.750 0.046		RA
Apr 23	245 4580.39	14.973 0.074		RA
May 01	245 4588.47	15.140 0.048		RA
May 06	245 4593.40	15.237 0.026		RA
May 08	245 4594.78		14.985 0.059	WW

Notes: RA = 40cm f/5 Newtonian + SXV-H9 CCD (R. Arbour, UK)
WW = 35cm C14 OTA + DSI Pro II w/Sony EXview HAD CCD (ICX 429) (W. Wiethoff, US)
KI = 60cm f/5.7 + Bitran BT-214E CCD (Kodak KAF-1001E) (K. Itagaki, Japan)

Table 3. Epoch of maximum, rise time to maximum and peak magnitude for the u' BVr' i' light curves of SN 2008ax

Band	JD (max)	Rise time (d)	M(λ)$_{\rm max}$
u'	245 4546.2 ± 0.4	17.4	14.65 ± 0.02
B	245 4547.7 ± 0.5	18.9	14.16 ± 0.03
g'	245 4549.3 ± 0.6	20.5	13.95 ± 0.02
V	245 4549.5 ± 0.5	20.7	13.51 ± 0.02
r'	245 4551.1 ± 0.5	22.3	13.38 ± 0.03
i'	245 4551.6 ± 0.6	22.8	13.26 ± 0.02
z'	245 4553.1 ± 1.0	24.3	13.28 ± 0.03

obtain $\mu = 29.92 \pm 0.29$ mag (i.e. $d = 9.6$ Mpc) which will be used throughout this paper.[3]

The reddening due to the Galaxy in the direction of NGC 4490 is very small [$E(B - V) = 0.022$ mag, Schlegel, Finkbeiner & Davis 1998]. However, there is evidence of additional reddening inside the host galaxy (see discussion in Section 4) and therefore we will adopt the value $E(B - V) = 0.3$ mag as the best estimate for the total extinction towards SN 2008ax.

The faint absolute magnitude measured at discovery (around −13.4) led Mostardi et al. (2008) to erroneously suggest that the SN was possibly an highly extinguished event or, alternatively, the superoutburst of a luminous blue variable. Instead, it was the first light coming from the explosion of one of the youngest stripped-envelope CC SNe ever discovered.

3 THE LIGHT CURVE

SN 2008ax is one of the best ever monitored core-collapse SNe, starting with a deep pre-explosion image obtained only 6 h prior to the SN discovery of Mostardi et al. (2008). The observational campaign of SN 2008ax started soon after the discovery and covered a period of about 70 d. Photometry has been obtained at the 2-m Liverpool Telescope (Steele et al . 2004) in La Palma (Canary Islands, Spain) and the 60-inch Telescope of the Palomar Observatory (Cenko et al. 2006). In addition, unfiltered data collected by amateur astronomers have been used in our analysis. These data have been scaled to the Johnson–Bessell V-band or the Sloan r'-band photometry, depending on the sensitivity curves of the CCDs used in these observations. We find that the quantum efficiency (QE) curve of the SXV-H9 CCD used by R.A. peaks around 5100 Å, so the unfiltered magnitudes of this images are best compared to the V-band magnitudes, while both the DSI Pro II and the KAF-1001E cameras used by W.W. and K.I., respectively, have CCDs with QEs peaking around 6000–6200 Å. Therefore, the unfiltered magnitudes obtained with these two imagers are scaled to the Sloan r' magnitudes.

Johnson–Bessell B and V, and Sloan u', g', r', i' and z' photometry of SN 2008ax is presented in Table 1, while the unfiltered amateurs' data are in Table 2. The resulting light curves (including the calibrated amateurs data) are shown in Fig. 2. Like in many H-stripped

[3]A consistency check can be done by considering the pair NGC 4485 and NGC 4490 as members of the 14-4 group. An accurate distance of the group was obtained by Tully et al. (2008) through a weighted average of four different methods tied to the *Hubble Space Telescope* (*HST*) Cepheid Key Project scale (Freedman et al. 2001). Rescaling for consistency to $H_0 = 72\,{\rm km\,s^{-1}\,Mpc^{-1}}$, a distance modulus $\mu = 29.91 \pm 0.13$ was obtained. This distance for the 14-4 group ($d \approx 9.6$ Mpc) is fully consistent with our average estimate for NGC 4490.

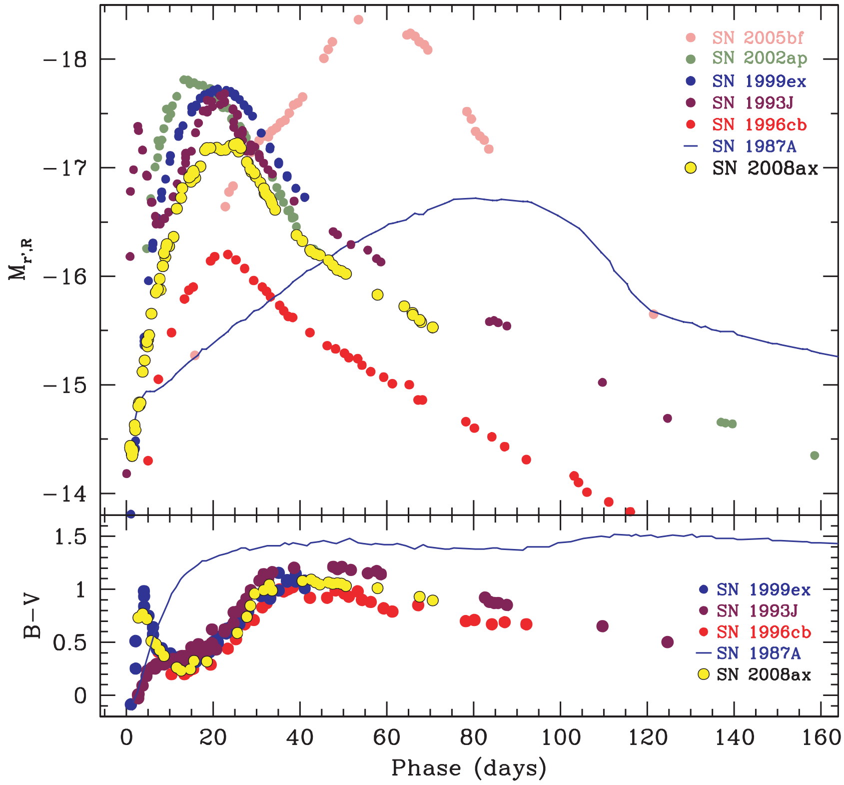

Figure 3. Top graph: *r*'-band absolute light curve of SN 2008ax, compared with the red band light curves of the peculiar Type Ib SN 2005bf (Folatelli et al. 2006), the broad-line Type Ic SN 2002ap (Gal-Yam et al. 2002; Yuzuru et al. 2002; Foley et al. 2003; Tomita et al. 2006), the normal Type Ib SN 1999ex (Stritzinger et al. 2002), the Type IIb SNe 1993J (Lewis et al. 1994; Barbon et al. 1995) and 1996cb (Qiu et al. 1999), and the peculiar Type IIP SN 1987A (Menzies et al. 1988; Catchpole et al. 1987, 1988). Bottom graph: $B-V$ colour evolution for SNe 2008ax, 1987A, 1996cb, 1993J and 1999ex.

Table 4. Log of spectroscopic observations.

Date	JD	Phase	Instrumental configuration	Exposure time (s)	Spectral range (Å)	Res. (Å)
Mar 12	245 4538.38	9.6	Wise 40-inch + FOSC + g600	2×3600	3990–8230	18
Mar 18	245 4544.35	15.6	Wise 40-inch + FOSC + g600	2×1800	3990–8240	18
Mar 29	245 4554.64	25.8	Palomar 200-inch + TSPEC	5×200	9500-13 500,14 050–18 150,19 230–24 670	[a]
Mar 31	245 4556.70	27.9	Palomar 200-inch + DBSP +g300+g316	2×60+2×120	3100–5480,5650–8170	9.5,13
Apr 01	245 4557.69	28.9	Palomar 200-inch + DBSP +g300+g316	3×60	3100–5470,5650–8170	6,7
Apr 02	245 4558.70	29.9	Palomar 200-inch + DBSP +g300+g316	3×60	3100–5460,5650–8170	7.5,9
Apr 08	245 4565.34	36.5	Wise 40-inch + FOSC + g600	3600	4010–8210	18
Apr 28	245 4584.64	55.8	Palomar 200-inch + DBSP +g600+g316	2×200	3130–5590,5640–9690	3.5,9.5

[a] 1.2 Å in the *J* band, 2.9 Å in the *K* band.

core-collapse SNe the peak luminosity in the blue bands is reached a few days earlier than in the red (about 19 d after the shock breakout in the *B* band and 23 in the *i*′ band, see Table 3). After maximum, the light curves decline rapidly in all bands until day ∼40, when the SN luminosity settles on to the radioactive tail.

H-poor core-collapse supernovae display a wide range of behaviour in their light curve evolution. In Fig. 3 (top graph), we compare the *r*′-band absolute light curve of SN 2008ax with those (Sloan *r*′ or Johnson–Bessell R) of a number of H-poor SNe (see caption of Fig. 3 for details). In particular, we note that the light curve of SN 2008ax is remarkably different from that of the peculiar Type II SN 1987A (that shares some early-time spectroscopic similarity with SN 2008ax, see Section 4). It is instead similar to those of the H-stripped core-collapse events shown in Fig. 3. The overall shape resembles that of the Type IIb SNe 1996cb and 1993J. In particular, its peak magnitude ($M_R \approx -17.3$ mag) is quite similar to that of SN 1993J (the difference is $\Delta M_R \approx 0.3$), but is significantly brighter (by ∼1 mag) than that of SN 1996cb. A major difference between the two SNe is that SN 2008ax does not show the prominent and narrow early-time peak exhibited by the light curve of SN 1993J. This peak is attributed to the initial shock heating and the subsequent cooling of a low-mass envelope (see e.g. Bartunov et al. 1994; Shigeyama et al. 1994). In SN 2008ax only a marginally detectable shoulder during the first day after shock breakout was observed, in analogy to that reported by Stritzinger et al. (2002) in the Type Ib SN 1999ex. This possibly due to SN 2008ax having an initial radius that was smaller than that of SN 1993J.

In Fig. 3 (bottom graph), we also compare the colour evolution of SN 2008ax with those of the Type II SN 1987A, the Type Ib SN 1999ex and the Type IIb SNe 1993J and 1996cb. SN 1987A has a

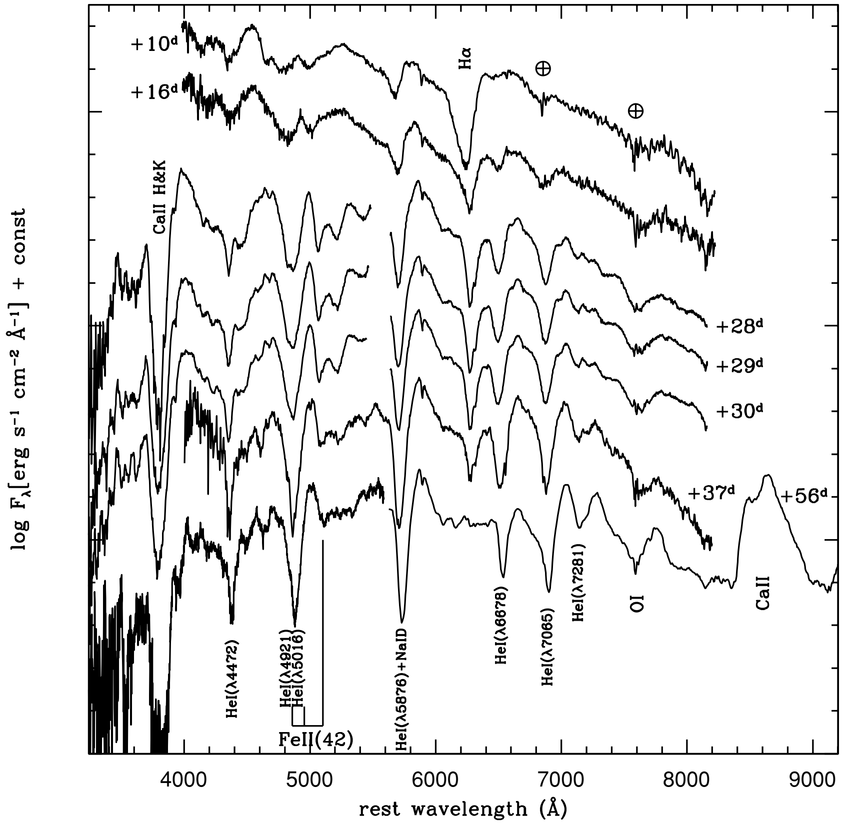

Figure 4. Spectral evolution of SN 2008ax. The most significant spectral lines and the epochs since core-collapse of the various spectra are also labelled. The spectra, corrected for total reddening $E(B - V) = 0.3$, are in the host galaxy rest frame. The positions of the most important telluric absorptions are also marked, with ⊕.

different colour evolution compared to the other three objects, that evolve in a rather similar fashion (apart from the early-time blue excess due to the shock breakout visible in SN 1993J). In particular, during the first 10 d SN 2008ax becomes rapidly bluer, moving from $B - V = 0.8$ to 0.2 (note that the colour evolution of SN 1993J follows the opposite trend in this phase). During the subsequent period, SN 2008ax (and the other Type Ib/IIb events in Fig. 3) becomes redder, reaching $B - V = 1.1$ at phase ∼40 d. Then, the colour becomes slowly bluer again with time.

4 THE METAMORPHOSIS OF SN 2008AX

SN 2008ax showed an amazing spectral evolution, transforming in a few weeks through many different spectral types. Blondin et al. (2008) initially classified it as a young 1987A-like Type II SN. The strong interstellar Na I D absorption visible in the spectrum of Blondin et al. (2008) also suggested significant host galaxy reddening, $E(B - V) = 0.6$. The presence of prominent H and He I lines, with blueshifted peaks, was indicative of very rapid spectral evolution, another characteristic in common with SN 1987A. The most important difference was the much broader spectral lines in SN 2008ax, corresponding to ejecta velocities in the range 23 000–26 000 km s^{-1}. In SN 1987A they were lower by a factor 2/3.

However, subsequent spectra showed increasing Fe II, Ca II and, most significantly, He I features, suggesting that this SN should be reclassified as a Type IIb (Chornock et al. 2008). Also, based on a new measurement of the EW of the Na I interstellar doublet (∼0.18 nm), Chornock et al. (2008) used an unspecified method to revise the estimate of the host galaxy contribution to the reddening to $E(B - V) = 0.5$ mag.

Marion et al. (2008), analysed a near-infrared (NIR) spectrum of SN 2008ax, and noted the presence of prominent He I features at 1.08 and 2.06 μm and a weak Paschen β. These features make this spectrum similar to the early-time NIR spectra of SN Ib 1999ex (Hamuy et al. 2002). The transition of SN 2008ax towards a Type Ib event was also revealed by optical spectra collected by Taubenberger et al. (2008). However, Taubenberger et al. (2008) pointed out that some H was still visible in their spectra, although less prominent than the stronger He I lines.

We collected a sequence of optical spectra of SN 2008ax using the 40-inch Telescope at the Wise Observatory (Israel) equipped with a Faint Object Spectrographic Camera (FOSC) and the 200-inch Hale Telescope at the Palomar Observatory (California, US) equipped with the Double Spectrograph (DBSP, Oke & Gunn 1982). The log of spectroscopic observations is in Table 4. All these spectra show relatively strong interstellar Na I D, whose equivalent width (EW) is about 1.8 Å, in excellent agreement with the value reported by Chornock et al. (2008). However, adopting the relation between *EW* and $E(B - V)$ derived by Turatto et al. (2003), we obtain $E(B - V) \approx 0.3$, which is significantly smaller than the reddening estimate of Blondin et al. (2008) and Chornock et al. (2008).

The metamorphosis of SN 2008ax, whose spectrum transitioned through different spectral types (II→IIb→Ib) is shown in Fig. 4, while a comparison with early spectra of the peculiar Type II-plateau SN 1987A, the normal SN Ib 1998dt and the Type IIb event 1987K is shown in Fig. 5 (two of these spectra have been downloaded from the

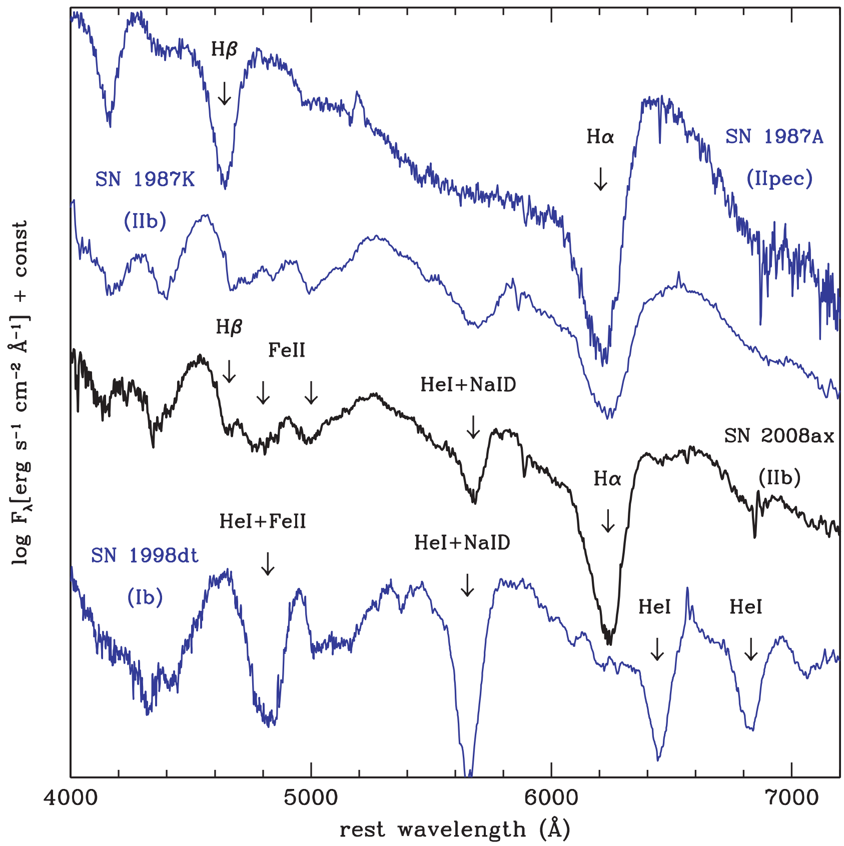

Figure 5. Comparison between the early-time (March 12) spectrum of SN 2008ax and those of the peculiar Type IIP SN 1987A (Pun et al. 1995), the Type IIb SN 1987K (Filippenko et al. 1988) and the normal Type Ib SN 1998dt (Matheson et al. 2001). The spectrum of SN 1987K, which provides the best match to the earliest spectrum of SN 2008ax, has been selected making use of the Superfit SN spectral identification code (Howell et al. 2005).

SUSPECT [4] data base). It is remarkable that the Hα feature, which is strong in the early-time spectra of SN 2008ax, progressively weakens and disappears ~2 months after core-collapse (Fig. 4). In this phase, the spectrum of SN 2008ax is that of a Type Ib SN. SN 1987K experienced an analogous 'identity crisis' (Filippenko et al. 1988), with the early-time spectra being rather similar to those of an H-rich Type II SN (e.g. 1987A, see Fig. 5) and very different from those of a canonical Type Ib. Some months later, however, SN 1987K evolved towards a spectrum dominated by Ca and O forbidden lines and not containing the Hα line in emission, which should be present in a Type II SN in the nebular phase. This wide-ranging spectral evolution seems to be quite common in Type IIb SNe: to a lesser extent, an analogous transition was seen in the spectra of SNe 1993J (Lewis et al. 1994; Barbon et al. 1995), 1996cb (Qiu et al. 1999) and 2001ig (Maund et al. 2007).

The evolution of the line velocities, measured from the position of the P-Cygni minima of He I 5876 Å, He I 7065 Å, Hα and Fe II 5169 Å is shown in Fig. 6, both for SN 2008ax and SN 1993J (data from Barbon et al. 1995). It is remarkable that the velocities of the two Type IIb SNe are comparable, although the velocity of Hα, after the initial drop, remains much higher in SN 2008ax than in SN 1993J, while that of Fe II 5169 Å is lower in SN 2008ax than in SN 1993J. This, and the evidence that Hα is missing in the spectrum obtained 2 months after the explosion, suggest that the H envelope is probably less massive in SN 2008ax than in SN 1993J

[4]http://bruford.nhn.ou.edu/~suspect/index1.html

SN 2008ax was also observed in the NIR a few days past maximum (on 2008 March 29) with the Triple Spectrograph (TSPEC, Wilson et al. 2004) mounted at the 200-inch Hale Telescope. This spectrum is compared with those of the Type Ib SN 1999ex and the Type II-plateau SN 1999em about 3–4 weeks after the explosion in Fig. 7. The most important H and He I lines in the NIR region are marked (the He I lines with dashed blue lines, the H lines with dot–dashed red lines). The most prominent feature in all the spectra is a P-Cygni line peaking around 10 900 Å. In SN 1999em this feature is likely due to a blend of Paschen γ and He I (with the possible contribution of C I, see Pastorello 2003), while in SNe 2008ax and 1999ex it is mostly He I 10 830 Å. Other He I lines identified in the spectra of both SNe 1999ex and 2008ax are at about 17 000 and 20 580Å. In agreement with what we find in the optical spectra, some H is also still visible in the NIR spectrum of SN 2008ax. Paschen β, which was prominent in SN 1999em, is indeed visible (though weak) in SN 2008ax at $\lambda \approx 12\,820$ Å, while it was not definitely detected in the Type Ib SN 1999ex. This is consistent with the classification of SN 2008ax as a Type IIb event.

5 DISCUSSION

Although the spectra of SN 2008ax are dominated by He I lines, the presence of H features in the early-time spectra is unequivocal (see Figs 4 and 7), suggesting that this SN should be classified as a Type IIb event. We showed in Sections 3 and 4 that SN 2008ax shares many similarities with other well-studied SNe IIb (e.g. 1993J and 1996cb). Nevertheless, the light curves of these SNe are also

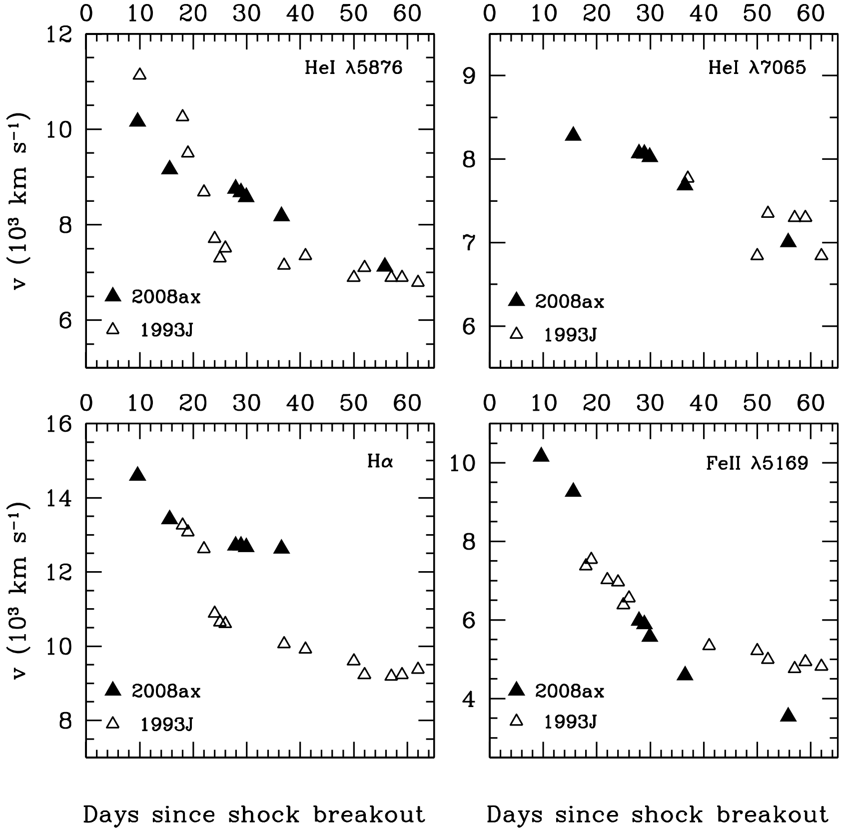

Figure 6. Evolution of line velocities for a few selected lines in SN 2008ax and SN 1993J. The data of SN 1993J are from Barbon et al. (1995).

similar to those of totally H-stripped SNe Ib (see Fig. 3), indicating that the presence of a residual H skin does not significantly affect the luminosity evolution of SNe IIb. The most significant difference between the light curves of Type Ib/ IIb SNe lies in their intrinsic luminosity, which is dependent on the amount of ^{56}Ni ejected in the explosion.

In order to estimate the ^{56}Ni mass synthesized by SN 2008ax, its quasi-bolometric (*uvoir*) light curve was computed and compared with that of SN 1993J. The *uvoir* light curve of SN 1993J was obtained by integrating the flux in the optical and NIR bands (using the data of Lewis et al. 1994; Barbon et al. 1995; Wada & Ueno 1997; Matthews et al. 2002). The observed optical light curve of SN 2008ax (Fig. 8, open red points) was rescaled, assuming for this object the same fractional NIR contribution to the *uvoir* light curve as SN 1993J (solid blue line). The *uvoir* light curve of SN 2008ax is shown in Fig. 8 with filled yellow symbols. Surprisingly, there is an excellent agreement in the *uvoir* luminosity between the two SNe. This is contrary to what we observed in individual bands (see e.g. Fig. 3), where SN 2008ax was slightly more luminous than SN 1993J in the blue bands and fainter in the red bands. The similar *uvoir* luminosity implies that the two objects have roughly the same mass of ejected ^{56}Ni. In SN 1993J the ^{56}Ni mass was around 0.07–0.11$_{\odot}$ (see discussion below), and this is also the ^{56}Ni mass range expected for SN 2008ax.

There is also a similarity in the overall shape of the light curves of SN 2008ax and SN 1993J, with the exception of the initial strong contribution of the shock breakout to the early time light curve of SN 1993J. This raises the issue of whether the progenitor and the explosion parameters are similar in these two SNe. The width of the light curve during the photospheric phase and the slope of the radioactive tail are known to depend on both the kinetic energy (E_k) and the ejected mass (E_{ej}) (Arnett 1982). In particular, the comparable widths of the light curve peaks of SNe 1993J and 2008ax suggest a similar value for the M_{ej}^3/E_k ratio (Arnett 1982), which, however, does not necessarily imply that M_{ej} and E_k are themselves similar.

Additional information on the individual values of M_{ej} and E_k could be obtained from the spectroscopy. The square of the photospheric velocity in envelope-stripped CC SNe is indeed proportional to the E_k/M_{ej} ratio (Arnett 1982). Since the velocity of the Fe II 5169 Å line is only marginally lower in SN 2008ax than in SN 1993J at the same phase (see Fig. 6, right-hand bottom panel), this may be an indication of comparable ejected masses and energies in the two SNe. Most theoretical papers on SN 1993J (e.g. Nomoto et al. 1993; Podsiaklowski et al. 1993; Woosley et al. 1994; Bartunov et al. 1994; Utrobin 1994; Shigeyama et al. 1994; Young, Baron & Branch 1995) converge towards a standard-energy explosion ($E_k \approx 10^{51}$ erg) of a 3-6 $M_{\odot}$ He core with a residual H skin (few $\times 10^{-1}\,M_{\odot}$). From an inspection of the observed SN properties, we therefore expect similar ejecta and explosion parameters for SN 2008ax.

An attempt to derive the ejecta mass and explosion energy was performed for the Type Ib SN 1999ex by Stritzinger et al. (2002) using a comparison with the 6C hydrogenless model of Woosley et al. (1987) for SNe Ib. Values of $M_{ej} \sim 5$–$6M_{\odot}$ and $E_k \approx 3 \times 10^{51}$ erg were derived for that SN. Recently, Soderberg et al. (2008) obtained similar values for the Type Ib SN 2008D: $M_{ej} \sim 5M_{\odot}$ and $E_k \approx 2 \times 10^{51}$ erg. However, the light curves of these two SNe are

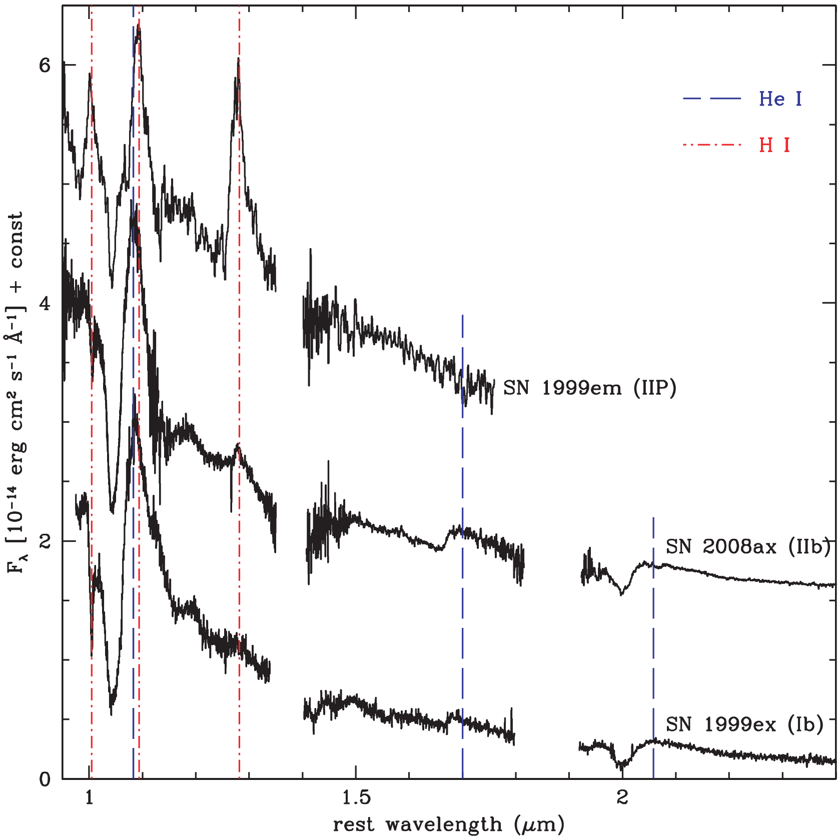

Figure 7. Comparison between the NIR spectrum of SN 2008ax obtained on April 29, and those of the Type IIP SN 1999em (Elmhamdi et al. 2003) and the normal Type Ib SN 1999ex (Stritzinger et al. 2002). The spectra of SNe 2008ax and 1999ex have been reddening corrected, while that of SN 1999em has been artificially reddened to make the comparison clearer. All spectra are in the host galaxy rest frame. The vertical dashed blue lines mark the expected rest position of the main He I lines, while the dot–dashed red lines mark the position of the Paschen δ, Paschen γ and Paschen β H lines.

slightly broader than that of 2008ax, whose shape, and hence likely its explosion and ejecta parameters, are probably closer to those of the Type IIb SNe 1993J and 1996cb.

Aldering et al. (1994), from an analysis of deep pre-explosion images, found that the progenitor of the Type IIb SN 1993J was a K supergiant. The SN precursor was an originally massive (12–17 $M_{\odot}$) member of a binary system, in which the two companions had comparable main sequence masses (Maund et al. 2004). In the case of SN 2008ax, the final configuration of the progenitor was likely a WR (WNL) star (either a single, massive WR or a lower-mass WR in an interacting binary system, see Crockett et al. 2008) with a residual H shell ($<0.1\,M_{\odot}$). The spectroscopic and photometric evolution of SN 2008ax agrees with this progenitor type.

Unlike SN 1993J, whose companion star was detected (Maund et al. 2004), the direct observation of the precursor of SN 2008ax in pre-explosion *HST* images does not (at present) allow us to definitely discriminate between a single star or a binary system. In the single-star scenario, the progenitor had a relatively high-mass (8–9$M_{\odot}$) C/O core and a final mass (C/O core + He/H envelope) in the range 11–13$M_{\odot}$ (Crockett et al. 2008). The mass of the C/O core was a factor of two times higher than that of the star that generated SN 1993J. This would imply that the progenitor of SN 2008ax was a star with a main sequence mass of about 25–30 $M_{\odot}$, significantly higher than the 12–17 $M_{\odot}$ estimated for SN 1993J. However, such a high C/O mass estimated for SN 2008ax would be expected to affect the shape of its light curve, making it broader than what is observed. This raises a potential problem in the interpretation of the observed SN evolution.

Alternatively, the progenitor could have been an initially less massive star (10–14$M_{\odot}$) in a binary system, embedded in a coeval cluster. In this case other objects are expected to contaminate the magnitude and colour estimates of the source at the position of the progenitor in the images analysed by Crockett et al. (2008). If this is true, multiple sources near the SN position will be eventually recovered in future observations of the explosion site.

6 CONCLUSIONS

SN 2008ax has a number of observational properties in common with other Type IIb SNe. In particular the shape of the optical light curves, the bolometric luminosity and the spectral line velocities resemble those of SN 1993J. This suggests for the two events similar explosion and ejecta parameters. However, the evolution of the spectra of SN 2008ax towards a totally H-deprived (Ib) spectral type is faster than in SN 1993J. In addition, SN 2008ax does not show the prominent early-time optical peak related to the shock breakout, and has slightly bluer colours compared with SN 1993J. This indicates that the two SNe are similar, but not identical.

Two different progenitors could produce SNe like 2008ax: a single, high-mass star that lost mass via strong stellar winds to become a massive WNL or, alternatively, a less-massive star that had its envelope stripped away through interaction with a companion star

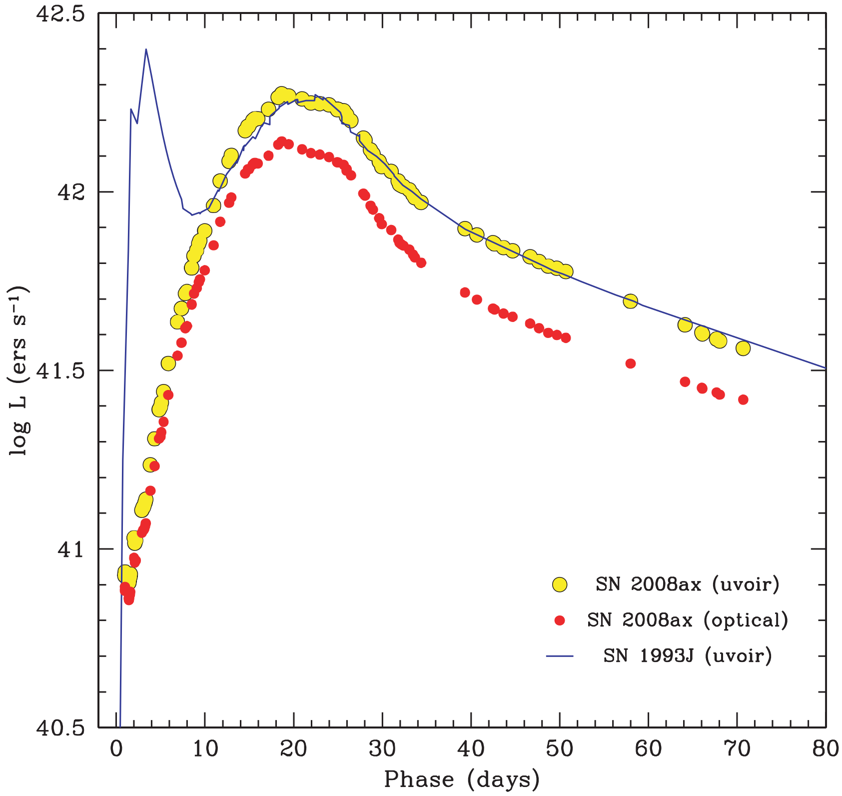

Figure 8. Comparison between the quasi-bolometric (*uvoir*) light curve of SN 2008ax (filled yellow symbols) with that of SN 1993J (solid blue line). Missing NIR (JHK) observations, the *uvoir* light curve of SN 2008ax has been obtained integrating the fluxes in optical bands (from u' to z', red points) and rescaled accounting the same NIR contribution as estimated for SN 1993J.

(Crockett et al. 2008). The latter scenario agrees better with the SN evolution.

Detailed modelling of the SN data is required to provide a robust estimate of the explosion and ejecta parameters, which is key information to finally unveil the nature of the WR star that exploded as SN 2008ax.

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REFERENCES

Aldering G., Humphreys R. M., Richmond M., 1994, AJ, 107, 662
Anupama G. C., Sahu D. K., Deng J., Nomoto K., Tominaga N., Tanaka M., Mazzali P. A., Prabhu T. P., 2005, ApJ, 631L, 125
Arbour R., 2008, CBET 1286, 2
Arnett W. D., 1982, ApJ, 253, 785
Barbon R., Benetti S., Cappellaro E., Patat F., Turatto M., Iijima T., 1995, A&AS, 110, 513
Bartunov O. S., Blinnikov S. I., Pavlyuk N. N., Tsvetkov D. Yu., 1994, A&A, 281L, 53
Benetti S., Branch D., Turatto M., Cappellaro E., Baron E., Zampieri L., Della Valle M., Pastorello A., 2002, MNRAS, 336, 91
Blondin S., Filippenko A. V., Foley R. J., Li W., Dessart L., 2008, CBET 1285
Branch D. et al., 2002, ApJ, 566, 1005
Catchpole R. M. et al., 1987, MNRAS, 229, 15
Catchpole R. M. et al., 1988, MNRAS, 231, 75
Cenko S. B. et al., 2006, PASP, 118, 1396
Chornock R., Filippenko A. V., Li W., Foley R. J., Stockton A., Moran E. C., Hodge J., Merriman K., 2008, CBET, 1298, 1
Clemens M. S., Alexander P., Green D. A., 1998, MNRAS, 297, 1015
Clemens M. S., Baxter K. M., Alexander P., Green D. A., 1999, MNRAS, 308, 364

Cohen J. G., Darling J., Porter A., 1995, AJ, 110, 308
Crockett et al., 2008, MNRAS, accepted (arXiv:0805.1913)
Deng J. S., Qiu Y. L., Hu J. Y., Hatano K., Branch D., 2000, ApJ, 540, 452
Elmhamdi A. et al., 2003, MNRAS, 338, 939
Elmhamdi A., Danziger I. J., Cappellaro E., Della Valle M., Gouiffes C., Phillips M. M., Turatto M., 2004, A&A, 426, 963
Filippenko A. V., 1988, AJ, 96, 1941
Filippenko A. V., 1997, ARA&A, 35, 309
Folatelli G. et al., 2006, ApJ, 641, 1039
Foley R. J. et al., 2003, PASP, 115, 1220
Foley R. J., Smith N., Gareshalingam M., Li W., Chorrock R., Filippenko A. V., 2007, ApJ, 657L, 105
Freedman W. L. et al., 2001, ApJ, 553, 47
Galama T. J. et al., 1998, Nat, 395, 670
Gal-Yam, Avishay, Ofek E. O., Shemmer O., 2002, MNRAS, 332L, 73
Hamuy M. et al., 2002, AJ, 124, 417
Howell D. A. et al., 2005, ApJ, 634, 1190
Huchtmeier W. K., Seiradakis J. H., Materne J., 1980, A&A, 91, 341
Immler S. et al., 2008, ApJ, 674L, 85
Lewis J. R. et al., 1994, MNRAS, 266, L27
Malesani D. et al., 2008, ApJL, submitted (arXiv:0805.1188)
Marion H., Garnavich P., Gerardy C. L., Rudy R. J., Lynch D. K., Russell R. W., Woodward C. E., 2008, CBET 1305, 1
Matheson T., Filippenko A. V., Chornock R., Leonard D. C., Li W., 2000, AJ, 119, 2303
Matheson T., Filippenko A. V., Li W., Leonard D. C., Shields J. C., 2001, AJ, 121, 1648
Matthews K., Neugebauer G., Armus L., Soifer B. T., 2002, AJ, 123, 753
Mattila S. et al., 2008, MNRAS, in press (doi:10.1111/j.1365-2966.2008.13516.x) (arXiv:0803.2145)
Maund J. R., Smartt S. J., Kudritzki R. P., Podsiadlowski P., Gilmore G. F., 2004, Nat, 427, 129
Maund J. R., Wheeler J. C., Patat F., Wang L., Baade D., Höflich P. A., 2007, ApJ, 671, 1944
Menzies J. D. et al., 1987, MNRAS, 227, 39
Mostardi R., Li W., Filippenko A. V., 2008, CBET, 1280
Nakano S., Itagaki K., 2008, CBET 1286, 1
Nomoto K., Suzuki T., Shigeyama T., Kumagai S., Yamaoka H., Saio H., 1993, Nat, 364, 507
Oke J. B., Gunn J. E., 1982, PASP, 94, 586
Pastorello A., 2003, PhD thesis, University of Padova
Pastorello A. et al., 2007, Nat, 447, 829
Pastorello A. et al., 2008a, MNRAS, in press (doi:10.1111/j.1365-2966.2008.13602.x) (arXiv:0801.2277)
Pastorello A. et al., 2008b, MNRAS, in press (doi:10.1111/j.1365-2966.2008.13603.x) (arXiv:0801.2278)
Paturel G., Bottinelli L., di Nella H., Fouque P., Gouguenheim L., Teerikorpi P., 1994, A&A, 289, 711
Paturel G., Petit C., Prugniel P., Theureau G., Rousseau J., Brouty M., Dubois P., Cambrésy L., 2003, A&A, 412, 45
Podsiaklowski P., Hsu J. J. L., Joss P. C., Ross R. R., 1993, Nat, 364, 509
Pun C. S. J. et al., 1995, ApJS, 99, 223
Qiu Y., Li W., Qiao Q., Hu J., 1999, AJ, 117, 736
Richmond M. W., Treffers R. R., Filippenko A. V., Paik Y., Leibundgut B., Schulman E., Cox C. V., 1994, AJ, 107, 1022
Roberts T. P., Warwick R. S., Ward M. J., Murray S. S., 2002, MNRAS, 337, 677
Ryder S. D., Sadler E. M., Subrahmanyan R., Weiler K. W., Panagia N., Stockdale C., 2004, MNRAS, 349, 1093
Ryder S. D., Murrowood C. E., Stathakis R. A., 2006, MNRAS, 369L, 32
Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ, 500, 525
Shigeyama T., Suzuki T., Kumagai S., Nomoto K., Saio H., Yamaoka H., 1994, ApJ, 420, 341
Smith N., Foley R. J., Filippenko A. V., 2007, ApJ, 680, 568
Soderberg A. M., Chevalier R. A., Kulkarni S. R., Frail D. A., 2006, 651, 1005
Soderberg A. M. et al., 2008, Nat, 453, 469
Steele I. A. et al., 2004, in Oschmann, Jacobus M., Jr., ed., Proc. SPIE Vol. 5489, Ground-Based Telescopes. SPIE, Bellingham WA, p. 679
Stritzinger M. D. et al., 2002, AJ, 124, 2100
Taubenberger S., Elias-Rosa N., Harutyunyan A., Navasardyan H., Benetti S., 2008, CBET, 1309, 1
Terry J. N., Paturel G., Ekholm T., 2002, A&A, 393, 57
Thronson H. A., Jr., Hunter D. A., Casey S., Harper D. A., Latter W. B., 1989, ApJ, 339, 803
Tominaga N. et al., 2005, ApJ, 633L, 97
Tominaga N. et al., 2008, ApJ, in press (arXiv:0711.4801)
Tomita H. et al., 2006, ApJ, 644, 400
Tully R. B., 1988, Nearby Galaxies Catalog, Cambridge Univ. Press, Cambridge and New York, 221 p.
Tully R. B., Shaya E. J., Karachentsev I. D., Courtois H. M., Kocevski D. D., Rizzi L., Peel A., 2008, ApJ, 676, 184
Turatto M., Cappellaro E., Benetti S., 2003, in Leibundgut B., Hillebrandt W., eds, Proc. ESO/MPA/MPE Workshop, ESO Astrophysics Symp., From Twilight to Highlight: The Physics of Supernovae. Springer-Verlag, Berlin, p. 200
Utrobin V., 1994, A&A, 281, L89
Van Dyk S. D., Garnavich P. M., Filippenko A. V., Höflich P., Kirshner R. P., Kurucz R. L., Challis P., 2002, PASP, 114, 1322
Viallefond F., Allen R. J., de Boer J. A., 1980, A&A, 82, 207
Wada T., Ueno M., 1997, AJ, 113, 231
Wilson J. C. et al., 2004, in Alan F. M. Moorwood and Iye Masanori, eds, Proc. SPIE, Vol. 5492, Ground-Based Instrumentation for Astronomy. SPIE, Bellingham WA, p. 1295
Woosley S. E., Pinto P. A., Martin P. G., Weaver T. A., 1987, ApJ, 318, 664
Woosley S. E., Eastman R. G., Weaver T. A., Pinto P. A., 1994, ApJ, 429, 300
Woosley S. E., Bloom J. S., 2006, ARA&A, 44, 507
Young T. R., Baron E., Branch D., 1995, ApJ, 449L, 51
Yoshii Y. et al., 2003, ApJ, 592, 467

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