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Photometric and spectroscopic study of a highly reddened type Ia supernova SN 2003hx in NGC 2076

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ABSTRACT

We present *UBVRI* CCD photometry and optical spectra of the type Ia supernova SN 2003hx which appeared in the galaxy NGC 2076, obtained till ∼ 146 d after the epoch of *B*-band maximum. The supernova reached at maximum brightness in *B* band on JD 245 2893 ± 1.0 with an apparent magnitude of 14.92 ± 0.01 mag which was estimated by making template fits to the light curves. SN 2003hx is an example of a highly reddened supernova with $E(B-V) = 0.56 \pm 0.23$. We estimate $R_v = 1.97 \pm 0.54$ which indicates the small size of dust particles as compared to their galactic counterparts. The luminosity decline rate is $\Delta m_{15}(B) = 1.17 \pm 0.12$ mag and the absolute *B*-band magnitude obtained from the luminosity versus decline rate relation (Phillips et al. 1999) is $M^B{}_{\rm max} = -19.20 \pm 0.18$ mag. The peak bolometric luminosity indicates that ∼0.66 $M_\odot$ mass of ^{56}Ni was ejected by the supernova. The spectral evolution indicates the supernova to be a normal type Ia event.

Key words: supernovae: general – supernovae: individual: SN 2003hx – galaxies: individual: NGC 2076.

1 INTRODUCTION

Type Ia supernovae (SNe Ia), being one of the most luminous stellar outburst, form a fairly homogeneous class of objects and are considered as standard candles for determining extragalactic distances and cosmological parameters. SNe Ia are produced by thermonuclear explosions of white dwarfs (Hoyle & Fowler 1960) primarily composed of carbon and oxygen nuclei. The probable explosion scenario involves a binary system in which a white dwarf accretes matter from its companion star until it reaches the Chandrasekhar mass limit of 1.4 $M_\odot$. Though SNe Ia show homogeneity in both their photometric as well as spectroscopic properties (Höflich et al. 1996) but many SNe show significant deviations. Li et al. (2001) studied a sample of SNe Ia and conclude that ∼64 per cent of them belong to the normal group, almost 20 per cent belong to the over luminous group of events such as SN 1991T whereas about 16 per cent belong to the sub luminous type such as SN 1991bg.

The last few decades have witnessed a large number of diverse data sets for SNe Ia. Nevertheless, SNe Ia seem to follow a few common patterns. One of these is the correlation between the peak luminosity and the linear decline rate (Phillips 1993). The colour evolution, spectral appearance and the host galaxy morphology are the other correlations. The peak absolute magnitude of type Ia SNe is correlated with the Hubble type of the parent galaxy. SNe Ia hosted by elliptical galaxies are comparatively fainter than SNe Ia in spirals (Della Valle & Panagia 1992; Howell 2001). Even amongst the normal group of type Ia SNe significant photometric and spectroscopic uncertainties exist. Nugent et al. (1995) saw that the spectral variations in type Ia SNe correlate with the expansion velocity, the effective temperature and the peak luminosity. Thus, it is not sufficient to describe SNe Ia by a single parameter such as the early light curve decline rather the diversity noticed is multidimensional (Hatano et al. 2000; Benetti et al. 2004). It is therefore, necessary to study the photometric and spectroscopic evolution of individual type Ia SNe.

The integrated flux in optical bands provides a meaningful estimate of the bolometric luminosity which is directly related to the amount of radioactive ^{56}Ni synthesized and ejected in the explosion (Arnett 1982; Höflich et al. 1996; Pinto & Eastman 2000a) which can later be used to test various explosion models of SNe Ia.

We present in this paper the optical photometric and spectroscopic observations of highly reddened type Ia supernova SN 2003hx. SN 2003hx was discovered on unfiltered KAIT images on 2003 September 12.5 UT (magnitude 14.3) and 13.5 UT (magnitude 14.4) by Burket, Papenkova & Li (2003). A KAIT image of the same region taken on 2003 March 7.2 UT shows nothing at the location of the SN to a limiting magnitude of ∼ 18.5. SN 2003hx is located at $\alpha = 05^{\rm h}46^{\rm m}46\overset{\rm s}{.}97$, $\delta = -16^\circ47'00\overset{''}{.}6$ (J2000) which is 5.2 arcsec

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west and 2.6 arcsec south of the nucleus of the galaxy NGC 2076. A spectrum of SN 2003hx taken on 2003 September 13.78 UT at the Australian National University (ANU) 2.3-m telescope shows it to be a type Ia supernova around maximum light (Salvo, Norris & Schmidt 2003). The Si II 635.5 nm line gives an expansion velocity of ∼12 000 km s^{-1} if the NED recession velocity for the host is adopted as 2142 km s^{-1} (Salvo et al. 2003). It was confirmed to be a type Ia supernova around 10 d past maximum light with the spectropolarimetric observations using the ESO very large telescope on 2003 September 15.4 UT (Wang & Baade 2003). The interstellar Na I D line has an equivalent width of 4.86 Å which indicates significant dust extinction. The observed degree of polarization is ∼2 per cent (Wang & Baade 2003). If this polarization is due to the dust in the host galaxy, then it implies that the dust particles are significantly smaller in size than their Galactic counterparts. These observations yield a value of 2.2 for the ratio of total to selective extinction, $R_v = A_v/E(B - V)$ (Wang & Baade 2003).

We have carried out the optical photometric and spectroscopic observations of the type Ia supernova SN 2003hx. A brief description of the observations and data analysis is given in Section 2, whereas the development of the light curves and colour curves are presented in Section 3. Section 4 discusses about the reddening estimate. The description about the absolute magnitude, the bolometric luminosity and the estimation of ^{56}Ni ejected are discussed in Section 5. Spectral evolution has been studied with a comparison to other type Ia supernovae in Section 6. Conclusion forms Section 7 of the paper.

2 OBSERVATIONS AND DATA REDUCTION

The observations of SN 2003hx were carried out with the 2-m Himalayan Chandra Telescope (HCT) at Indian Astronomical Observatory (IAO), Hanle during 2003 September 18 to 2004 February 03 which was 6 d after the discovery on 2003 September 12. The Himalayan Faint Object Spectrograph Camera (HFOSC) equipped with the SITe 2000 × 4000 pixel CCD was used. The central 2000 × 2000 region was used for imaging covering a field of 10 × 10 arcmin^2 on the sky corresponding to a plate scale 0.296 arcsec pixel^{-1}. The gain and readout noise of the CCD camera are 1.22 e$^-$ ADU^{-1} and 4.87 e$^-$, respectively.

2.1 Photometry

The broad-band *UBVRI* photometric observations of SN 2003hx were carried out at 16 epochs during 2003 September 18 to 2003 February 03. All the images were bias subtracted, flat-fielded and cosmic ray removed in the standard fashion using various tasks in IRAF. Landolt (1992) standard region PG 0231+051 was imaged along with the supernova field in *UBVRI* filters on 2005 October 26 under good photometric sky conditions. The values of atmospheric extinction on the night of 2005 October 26/27 determined from the observations of PG 0231+051 bright stars are 0.30 ± 0.01, 0.20 ± 0.009, 0.12 ± 0.007, 0.08 ± 0.004 and 0.04 ± 0.003 in U, B, V, R and I filters, respectively. The observations of PG 0231+051 were used to generate secondary standards in the supernova field. The *UBVRI* magnitudes of 10 secondary stars using the transformation equations obtained are listed in Table 1 and are marked in Fig. 1. These magnitudes were used to calibrate the data obtained on other nights. The sequence photometry of SN 2003hx field was carried out by the American Association of Variable Star Observers (AAVSO). We compared our field calibration with that of AAVSO and found it to be consistent. Thus, our calibration of SN 2003hx field is secure.

We performed aperture photometry on the local standards using an aperture of 3–4 times the full width at half-maximum (FWHM) of the seeing profile that was determined on the basis of an aperture growth curve. Accurate estimate of sky and its subtraction plays a crucial role in the photometry when the object falls on the varying background. The supernova was just next to the nucleus of the galaxy, we therefore had to perform template subtraction to get a better estimate of the underlying background. The template observations were taken with the same instrumental set-up, on 2005 October 26, nearly two years after the supernova discovery, when the supernova had faded. These templates were subtracted from the images of SN obtained during 2003–2004. One such subtracted image, showing only the supernova SN 2003hx, is shown in Fig. 2. When the seeing was not very good, the template subtraction was not perfect and showed signature of the galaxy. Here, the supernova magnitudes were determined by using the profile-fitting method with a fitting radius equal to that of the FWHM of the seeing profile. The difference between the aperture and profile-fitting magnitudes was obtained using standards and was applied to the supernova magnitudes. Thus, the supernova magnitudes were obtained by differentially calibrating with respect to the secondary standards listed in Table 1. The supernova magnitudes derived in this way are given in Table 2.

2.2 Spectroscopy

Spectroscopic observations of SN 2003hx were carried out on four nights starting 2003 September 19 which was 7 d after the discovery on 2003 September 12. The log of spectroscopic observations is given in Table 3. All the spectra were obtained at a resolution

Table 1. Magnitudes for the sequence of secondary standard stars in the field of SN 2003hx. The stars are identified in Fig. 1.

ID	*U*	*B*	*V*	*R*	*I*
1	17.17 ± 0.07	16.22 ± 0.01	15.20 ± 0.01	14.65 ± 0.02	14.12 ± 0.01
2	15.43 ± 0.07	15.60 ± 0.01	15.09 ± 0.01	14.74 ± 0.02	14.36 ± 0.01
3	16.58 ± 0.07	16.51 ± 0.01	15.88 ± 0.01	15.48 ± 0.02	15.07 ± 0.01
4	16.52 ± 0.07	16.74 ± 0.01	16.29 ± 0.01	15.96 ± 0.02	15.63 ± 0.01
5	16.09 ± 0.07	15.95 ± 0.01	15.32 ± 0.01	14.91 ± 0.02	14.51 ± 0.01
6	16.29 ± 0.07	16.13 ± 0.01	15.47 ± 0.01	15.08 ± 0.02	14.63 ± 0.01
7	14.66 ± 0.07	14.65 ± 0.01	14.14 ± 0.01	13.81 ± 0.02	13.48 ± 0.01
8	16.58 ± 0.07	16.10 ± 0.01	15.81 ± 0.01	15.42 ± 0.02	15.02 ± 0.01
9	15.10 ± 0.07	14.70 ± 0.01	13.96 ± 0.01	13.52 ± 0.02	13.13 ± 0.01
10	17.29 ± 0.07	16.92 ± 0.01	16.24 ± 0.01	15.84 ± 0.02	15.42 ± 0.01

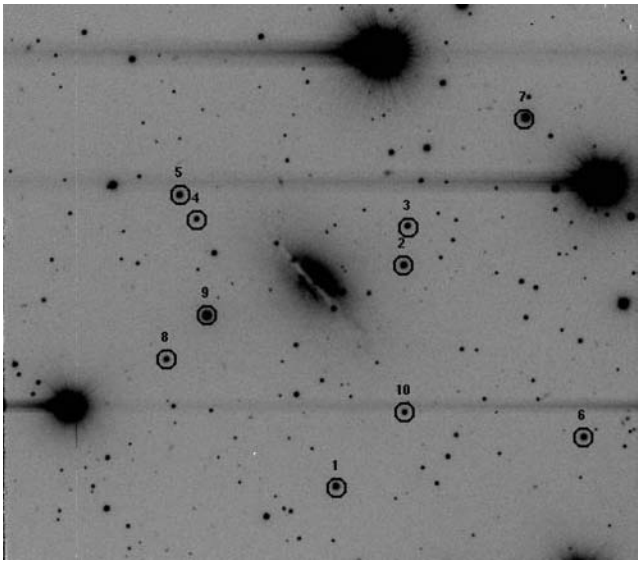

Figure 1. A 10 × 10-arcmin^2 field of SN 2003hx. The 10 secondary stars used for calibration are marked. North is up and east is to the left-hand side.

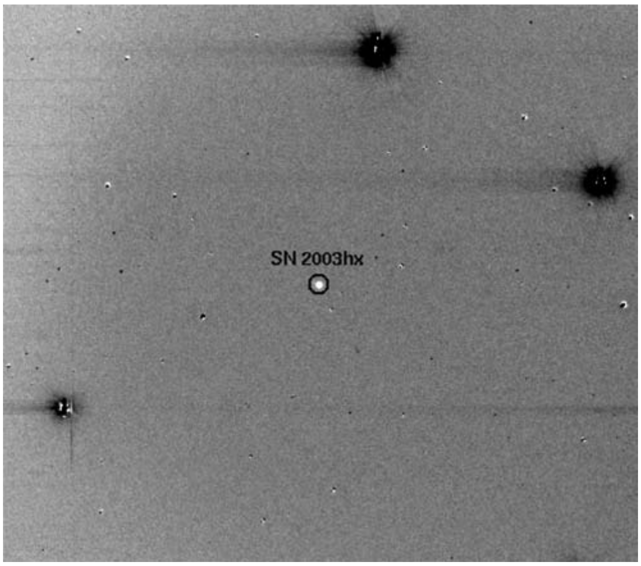

Figure 2. Supernova SN 2003hx after the template subtraction.

of ∼7 Å in the wavelength range 3300–6000, 3500–7000, 5200–9200 and 5200–10 300 Å. Spectroscopic data were reduced using the standard routines within IRAF. The data were bias corrected, flat-fielded and the one-dimensional spectra were extracted using the optimal extraction method. FeAr and FeNe sources were used for wavelength calibration. The wavelength calibrated spectra were corrected for instrumental response using spectra of spectrophotometric standards observed on the same night and brought to the same flux scale. The final spectrum on a relative flux scale was obtained by combining the flux calibrated spectra in the two different regions scaled to a weighted mean.

3 LIGHT CURVES AND COLOUR CURVES

In this section we study the multiband light curve and colour curve evolution of SN 2003hx and compare it with other type Ia supernovae.

3.1 *UBVRI* light curves

We present the *UBVRI* light curves of SN 2003hx in Fig. 3. Since our observations started ∼6 d after the discovery, we do not have observations around the peak brightness. The peak brightness and the JD corresponding to the peak brightness in different bands was estimated by making template fits to the observations. Our observations span a period of ∼ 150 d. The frequency distribution of our data is *N(U, B, V, R, I)* = (3, 11, 16, 14, 13). In order to determine peak brightness in different bands we have adopted the template fitting method. We attempted to fit the different template sets in *BVI* bands given by Hamuy et al. (1996). We adopted a χ^2 minimizing technique which solved simultaneously for the peak magnitude and the peak time in different bands. We see that the *B*-band fits best with the template of SN 1992al whereas the lowest value of χ^2 is attained in the case of SN 1992A for *V* and *I* bands. Since Hamuy et al. (1996) does not present the *R*-band template, we have taken the *R*-band template for type Ia supernova from Schlegel (1995). The *R*-band template was similarly fit to the observations to determine the peak magnitude and the peak time in *R* band. Fig. 4 shows the light curves in *BVRI* bands including the template fits to the data.

The main parameters of SN 2003hx as estimated from template fits are listed in Table 4. Leibundgut (1988) showed that for a normal type Ia supernova, a 2 d difference is seen between the time of maxima in the *B* and *V* bands. We see from the template fits that SN 2003hx reached maximum brightness in the *V*, *R* and *I* bands earlier than in the *B* band. An excellent match of the SN 1992al template with that of SN 2003hx indicates that the peak in the *B* band occurred at JD 245 2893 ± 1.0. These peak magnitudes obtained using template fitting are further used to calculate the peak luminosity in Section 5.

In Fig. 4 we see a pronounced secondary maximum for SN 2003hx in the *I* band. This secondary maximum was seen ∼21 d after the *B* maximum and was 0.32 mag fainter than the first maximum. The magnitude of the secondary *I* maxima is listed in Table 4. *R* band also shows a noticeable rise similar to the *I* band at similar epochs. This secondary maxima in the *I* band is a remarkable feature of type Ia SNe and becomes more pronounced in the near-infrared (near-IR) band. Such behaviour has been seen for many type Ia SNe. Elias et al. (1981) and Pinto & Eastman (2000b) pointed out that this secondary maximum is due to a temporary increase in absorption, which reduces with the fall in the degree of ionization several weeks after maximum light.

$\Delta m_{15}(B)$, the number of magnitudes in the *B* band by which the SN declines in the first 15 d after maximum, is a characteristic feature of the type Ia SNe. The fitted template of SN 1992al has a $\Delta m_{15}(B) = 1.11$. We calculate $\Delta m_{15}(B) = 1.17 \pm 0.12$ by taking the *B*-band peak magnitude obtained by the template fit and the observed *B*-band magnitude ∼15 d after the *B* maximum. The average decline rate in different bands is also estimated, and listed in Table 4, from our observations using a time baseline of 20 d.

3.2 Colour curves

Supernovae of type Ia show significant uniformity in their intrinsic colours in late epochs after maximum light. The dereddened $(B - V)$, $(V - R)$ and $(R - I)$ colour curves of SN 2003hx are shown in Figs 5–7. The colour curves of SN 2003hx are dereddened using the total extinction values listed in Table 4 and discussed in Section 4. For a comparison, we show here the colour curves of

Table 2. Photometric observations of SN 2003hx.

Date	JD 240 0000+	Phase[a] (d)	U	B	V	R	I
18/09/03	52901.4769	8.47	16.20 0.03	15.07 0.03	15.07 0.03	14.98 0.03	14.89 0.02
20/09/03	52903.4866	10.46		15.24 0.03	15.19 0.05	14.93 0.04	
21/09/03	52904.4847	11.48		15.34 0.04	15.22 0.05	14.94 0.05	14.73 0.04
22/09/03	52905.4805	12.48		15.46 0.03	15.12 0.03	14.89 0.02	14.53 0.02
27/09/03	52910.4865	17.48		16.09 0.22	15.46 0.05	14.87 0.04	14.40 0.03
28/09/03	52911.4870	18.48		16.23 0.06	15.63 0.05	14.90 0.04	14.30 0.06
06/10/03	52919.4786	26.47	17.11 0.21		16.17 0.02	15.51 0.01	15.17 0.03
18/10/03	52931.4155	38.41		18.06 0.03	16.65 0.03	16.34 0.02	15.99 0.05
27/10/03	52940.3899	47.38		18.23 0.02	16.93 0.03	16.68 0.03	16.44 0.04
01/11/03	52945.4695	52.46		18.28 0.01	17.09 0.02	16.81 0.04	16.64 0.05
02/11/03	52946.4872	53.48			17.12 0.04	16.85 0.03	16.71 0.06
07/11/03	52951.2987	58.29	18.07 0.10	18.30 0.03	17.18 0.02		16.73 0.04
18/11/03	52962.4231	69.42			17.45 0.02	17.27 0.02	
04/01/04	53009.2533	116.25			18.56 0.04	18.52 0.06	18.12 0.11
27/01/04	53031.1773	138.17		19.41 0.05	18.85 0.08		18.17 0.08
03/02/04	53039.1489	146.14			19.24 0.06	19.23 0.10	

[a]Relative to the epoch of B maximum (this work) JD = 245 2893.0.

Table 3. Spectroscopic observations of SN 2003hx.

Date	JD 240 0000+	Phase[a] (d)	Range (Å)
19/09/03	245 2902.4769	9.47	3300–6000; 5200–10 300
22/09/03	245 2905.4805	12.48	3500–7000; 5200–9200
24/09/03	245 2907.1805	14.18	3500–7000; 5200–9200
02/11/03	245 2946.4872	53.48	3500–7000; 5200–9200

[a]Relative to the epoch of B maximum JD = 245 2893.0.

other type Ia supernovae, which were reddening corrected using Cardelli extinction law (Cardelli, Clayton & Mathis 1989) and the $E(B-V)$ values of $E(B-V) = 0.026$ (galactic reddening only using Schlegel, Finkbeiner & Davis 1998) for SN 1990N, $E(B-V) = 0.13$ for SN 1991T (Phillips et al. 1992), $E(B-V) = 0.04$ for SN 1994D (Richmond et al. 1995), $E(B-V) = 0.32$ for SN 1998bu (Hernandez et al. 2000), $E(B-V) = 0.032$ for SN 1999aw (Strolger et al. 2002), $E(B-V) = 0.5$ for SN 2000E (Valentini et al. 2003), $E(B-V) = 0.044$ for SN 2002hu (Sahu, Anupama & Prabhu 2006), $E(B-V) = 0.02$ for SN 2003du (Anupama, Sahu & Jose 2005) and $E(B-V) = 0.18$ for SN 2004S (Misra et al. 2005).

The evolution of $(B-V)_0$ colour of SN 2003hx is significantly different than other type Ia supernovae, however the overall trend

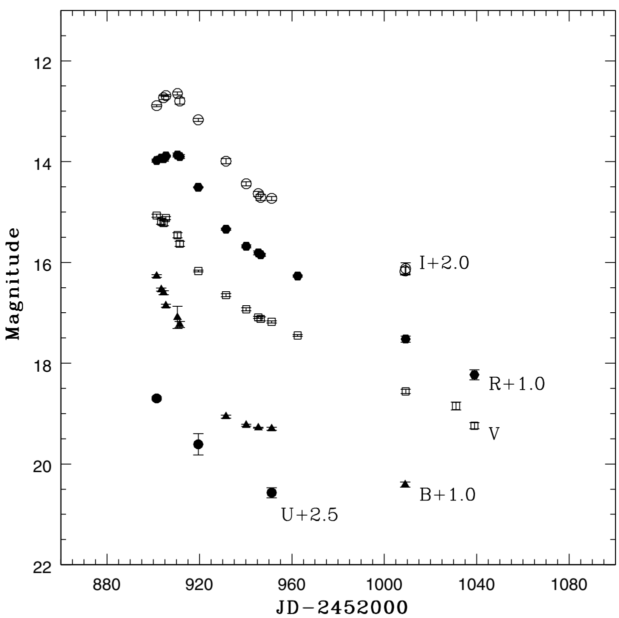

Figure 3. *UBVRI* light curve of SN 2003hx. The light curves are offset by a constant value on the magnitude scale as indicated in the plot.

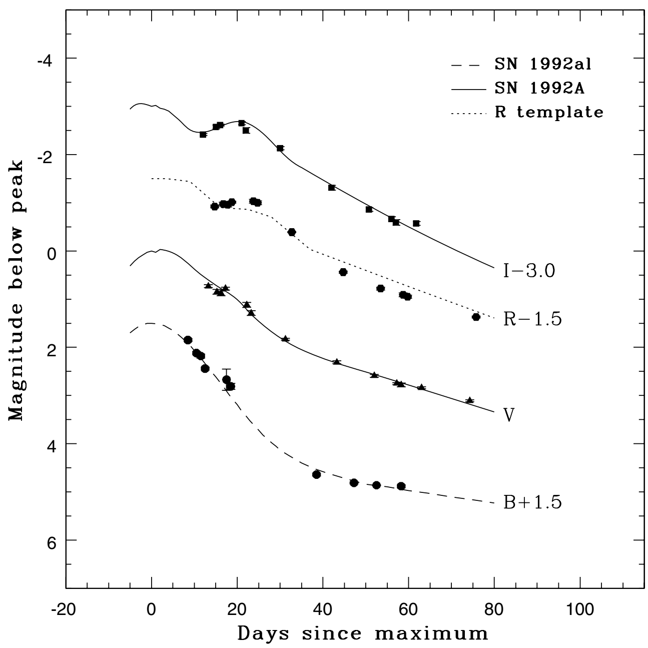

Figure 4. *BVRI* light curves of SN 2003hx with the best fitting templates of Hamuy et al. (1996) in the *BVI* bands and Schlegel (1995) in the *R* band. *B*-band light curve fits best with SN 1992al template [dashed line: $\Delta m_{15}(B) = 1.11$] whereas the *V* and *I* light curve fit best with SN 1992A template (solid line). The *R*-band template is shown by dotted lines. The light curves are offset by a constant value on the magnitude scale as indicated in the plot for clarity.

Table 4. Parameters of SN 2003hx.

Discovery date	2003 September 12.5 UT
Host galaxy	NGC 2076
Galaxy type	Morphological type S0-a
RA (2000)	$05^{h}46^{m}46\overset{s}{.}97$
Dec. (2000)	$-16°47'00\overset{''}{.}6$
Offset from the nucleus	5.2 arcsec west and 2.6 arcsec south
Spectrum	Type Ia
Radial velocity from galaxy redshift (km s^{-1})	2142 ± 5 (NED)
	2137 ± 7 (LEDA)
Radial velocity corrected for LG infall on to Virgo (km s^{-1})	1967 (LEDA)
Expansion velocity of the SN	12 000 km s^{-1}
Distance modulus ($H_0 = 65$ km s^{-1} Mpc^{-1})	32.456 mag
Epoch of maximum (from template fitting)	B band $245\,2893.0 \pm 1.0$
	V band $245\,2888.3 \pm 0.5$
	R band $245\,2886.7 \pm 1.0$
	I band $245\,2889.6 \pm 0.6$
Magnitude at maximum	$B = 14.92 \pm 0.01$
	$V = 14.34 \pm 0.03$
	$R = 14.40 \pm 0.06$
	$I = 14.30 \pm 0.03$
Colours at maximum	$B - V = 0.58 \pm 0.03$
	$V - R = -0.06 \pm 0.06$
	$R - I = 0.10 \pm 0.06$
Absolute magnitudes at maximum	$M^B = -19.20 \pm 0.18$
	$M^V = -19.22 \pm 0.15$
	$M^R = -18.91 \pm 0.22$
	$M^I = -18.70 \pm 0.17$
Reddening estimate: Using Δm_{15} and intrinsicn luminosity Phillip's relation	$E(B - V) = 0.56 \pm 0.23$
Phillip's relation	$E(B - V) = 0.64 \pm 0.12$
	$E(V - I) = 0.35 \pm 0.12$
Lira's relation	$E(B - V) = 0.43 \pm 0.04$
Using intrinsic colours of Nobili et al. (2003) at maximum	$E(B - V) = 0.69 \pm 0.03$
	$E(V - I) = 0.47 \pm 0.04$
$R_v = 1.97 \pm 0.54$	
Adopted total extinction (mag)	$A_B = 1.664$
	$A_V = 1.104$
	$A_R = 0.858$
	$A_I = 0.543$
Magnitude of secondary I maximum (from template fitting)	14.62
Δm_{15} in B from template	1.11
Δm_{15} in B from observations	1.17 ± 0.12
Decline rate per day	B band 0.092 ± 0.06
	V band 0.051 ± 0.05
	R band 0.072 ± 0.04
	I band 0.059 ± 0.07

40 d past B maximum is the same as other type Ia supernovae. At the epoch of B-band maximum, $(B - V)_0 = 0.02$ mag which is consistent with the intrinsic colours at maximum observed for other type Ia supernovae usually in the range of ~ -0.1 to $+0.1$ mag. Type Ia supernovae attain $(B - V)_0 = 1$ mag $\sim$30 d after B maximum. We do not have colour estimate at $\sim$30 d post B-band maximum, however $(B - V)_0 = 0.85$ at $\sim$38 d after B maximum. After this epoch the colour gets bluer as also seen for other supernovae of type Ia. The overall $(B - V)_0$ colour evolution of SN 2003hx is not bluer as seen in Fig. 5 for other supernovae.

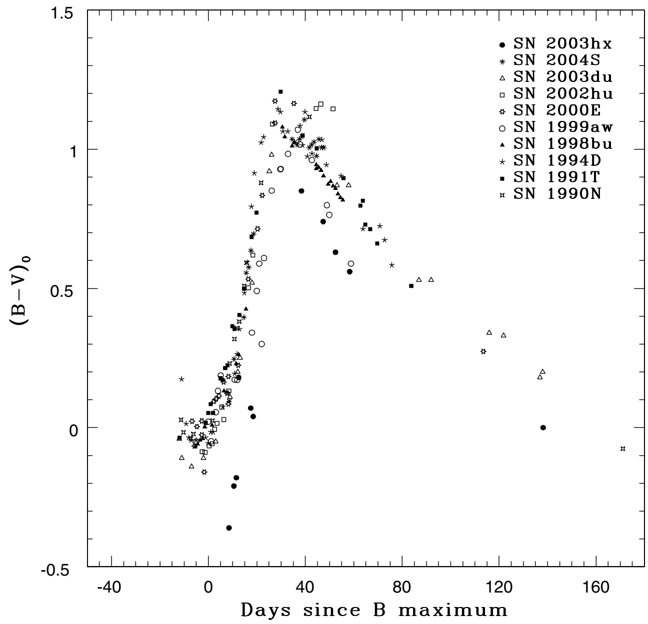

Figure 5. The intrinsic $B - V$ colour evolution of SN 2003hx compared with other supernovae of type Ia. The adopted reddening value for each supernova is mentioned in the text.

The $(V - R)_0$ colour curves of SN 2003hx also evolves in a manner similar to other SNe Ia. However, the colours of SN 2003hx are quite similar to SN 1999aw till $\sim$20 d after B-band maximum. The early $(V - R)_0$ colour is bluest at -0.16 mag $\sim$ 8 d past B-band maximum although bluer $(V - R)_0$ colour is observed after 80 d after B maximum. $(V - R)_0$ reaches 0.48 mag after $\sim$18 d after B maximum which is quite different as compared to other typical type Ia supernovae (Fig. 6).

The $(R - I)_0$ colour evolution of SN 2003hx follows the similar trend as seen for other type Ia supernovae compared here. The evolution of $(R - I)_0$ colour of SN 2003hx till $\sim$30 d after B

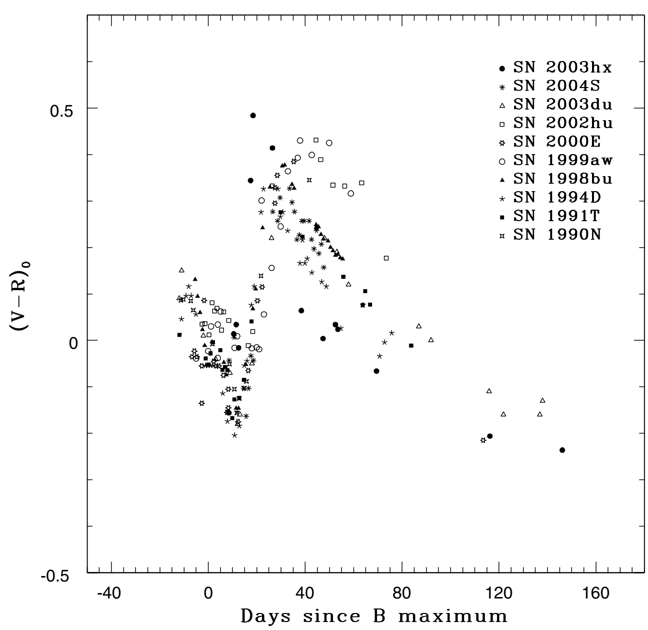

Figure 6. The intrinsic $V - R$ colour evolution of SN 2003hx compared with other supernovae of type Ia.

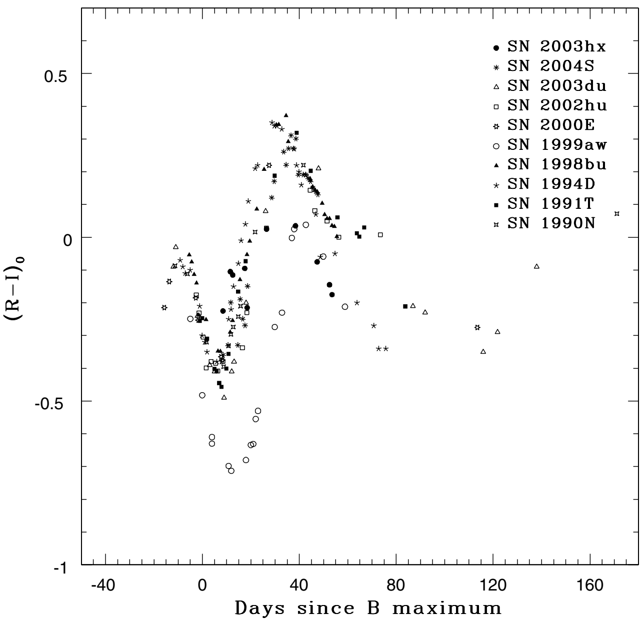

Figure 7. The intrinsic $R - I$ colour evolution of SN 2003hx compared with other supernovae of type Ia.

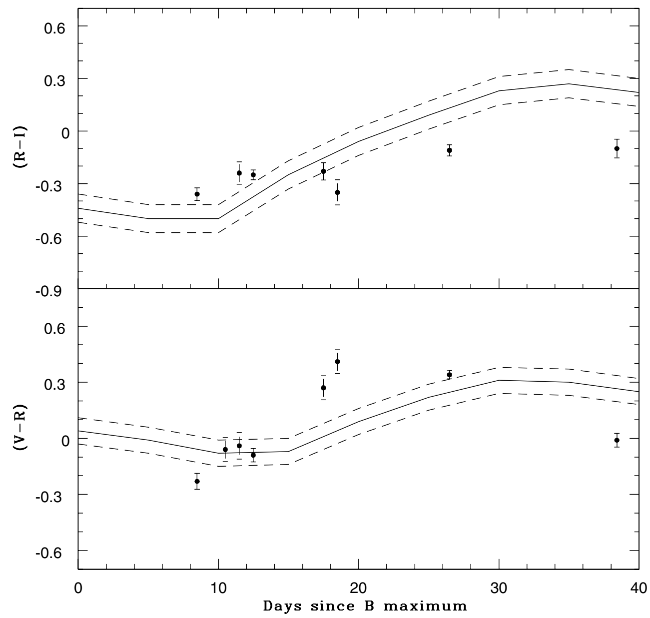

Figure 8. $(V - R)$ and $(R - I)$ colour curves of SN 2003hx. Filled circles represent colours obtained from our observations which have been corrected for the best fit value of selective extinction. The middle (solid) line in each panel shows the intrinsic colour curves of Nobili et al. (2003) bounded by errors on both sides (dashed line).

maximum is similar to other type Ia supernovae, but after 30 d the $(R - I)_0$ colours are generally bluer than the other supernovae. The $(R - I)_0$ colour reaches its bluest value of −0.23 mag around 8 d after *B* maximum and subsequently gets redder after that.

Comparing $(B - V)_0$, $(V - R)_0$ and $(R - I)_0$ colours of different type Ia supernovae, we see that the $(B - V)_0$ and $(R - I)_0$ colour evolution of SN 2003hx is quite close to the respective colours of SN 1999aw.

We also compare the colours of SN 2003hx with those obtained using the intrinsic colour curves of the SNe Ia population given by Nobili et al. (2003). Nobili et al. (2003) present the intrinsic colour curves of 48 type Ia SNe till 40 d after *B*-band maximum. The total selective extinction was estimated, taking it as a fit parameter, by comparing the observed colours of SN 2003hx with the intrinsic colours given by Nobili et al. (2003). The overall shape of the observed $(V - R)$ and $(R - I)$ colour curves are similar to the intrinsic colour curves (Fig. 8), except for systematic shifts in individual colours due to selective extinction. Best fitting value of selective extinction obtained are $E(V - R) = 0.32 \pm 0.07$ and $E(R - I) = 0.45 \pm 0.08$. Reddening estimates from other methods are discussed in Section 4 and listed in Table 4.

3.3 Comparison of the light curves

In Figs 9–12 we compare the *BVRI* light curves, respectively, of SN 2003hx with other normal type Ia SNe: SN 1990N [$\Delta m_{15}(B) = 1.03$, Lira et al. 1998], SN 1991T [$\Delta m_{15}(B) = 0.95$, Lira et al. 1998], SN 1994D [$\Delta m_{15}(B) = 1.26$, Richmond et al. 1995], SN 1998bu [$\Delta m_{15}(B) = 1.01$, Suntzeff et al. 1999], SN 1999aw [$\Delta m_{15}(B) = 0.81$, Strolger et al. 2002] SN 2000E [$\Delta m_{15}(B) = 0.94$, Valentini et al. 2003], SN 2002hu [$\Delta m_{15}(B) = 1.00$, Sahu et al. 2006], SN 2003du [$\Delta m_{15}(B) = 1.04$, Anupama et al. 2005] and SN 2004S [$\Delta m_{15}(B) = 1.26$, Misra et al. 2005]. All the light curves have been plotted by normalizing to the epoch of *B*-band maximum for each supernova and the respective peak magnitudes in different bands. Comparison of the *BVRI* light curves of SN 2003hx shows that they are quite similar to other type Ia SNe till ∼ 20 d after *B*-band maximum whereas at a later epoch they are fainter than other SNe Ia. The *B*-band light curve is similar to SN 2004S 20 d after *B*-band maximum. Post 20 d after *B* maximum, the *VRI* light curves of SN 2003hx are very similar to those of SN 1994D which is a normal type Ia SNe with a decline rate of $\Delta m_{15}(B) =$

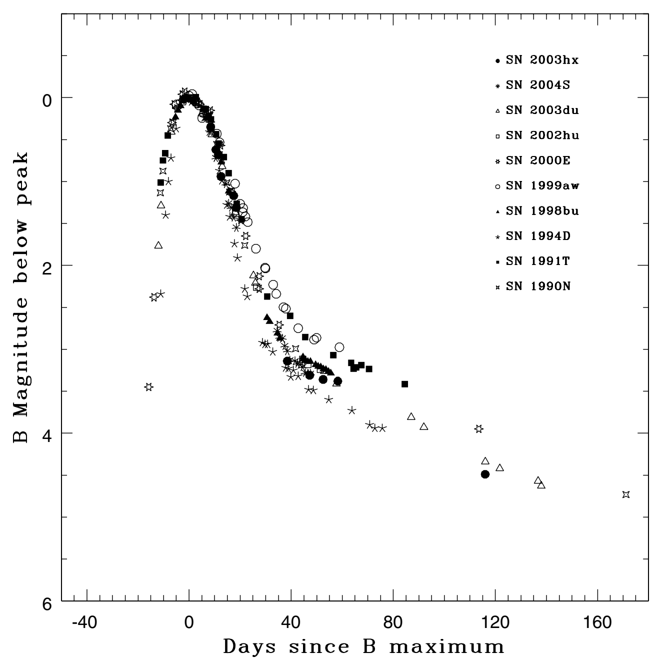

Figure 9. *B*-band light curve of SN 2003hx together with those of SN 2004S, SN 2003du, SN 2002hu, SN 2000E, SN 1999aw, SN 1998bu, SN 1994D, SN 1991T and SN 1990N. All the light curves are shifted to match the time of *B* maximum and peak magnitude in *B* band.

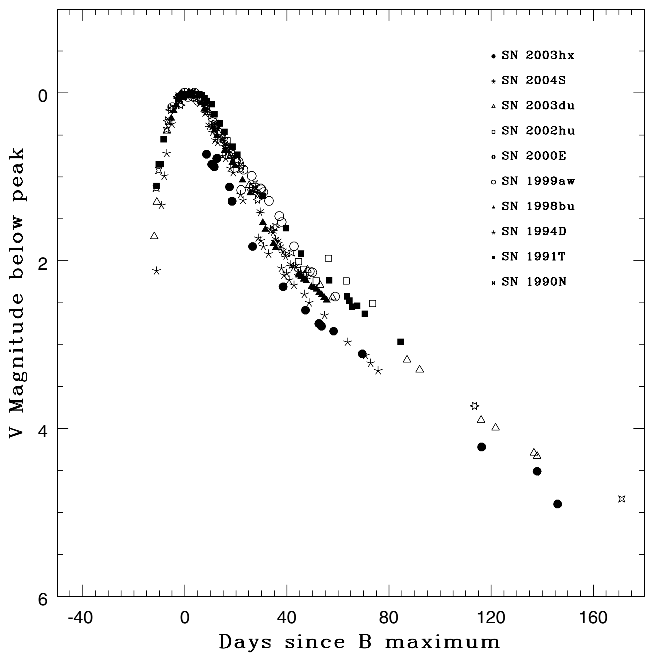

Figure 10. *V*-band light curve of SN 2003hx together with those of SN 2004S, SN 2003du, SN 2002hu, SN 2000E, SN 1999aw, SN 1998bu, SN 1994D, SN 1991T and SN 1990N. All the light curves are shifted to match the time of *B* maximum and peak magnitude in *V* band.

1.26 mag. 80 d after *B* maximum SN 2003hx compares well with the light curves of SN 2003du. Both SN 2003hx and SN 1994D were hosted by lenticular galaxies NGC 2076 and 4256, respectively. The light curve parameter $\Delta m_{15}(B)$ for different type Ia SNe is listed in Table 5.

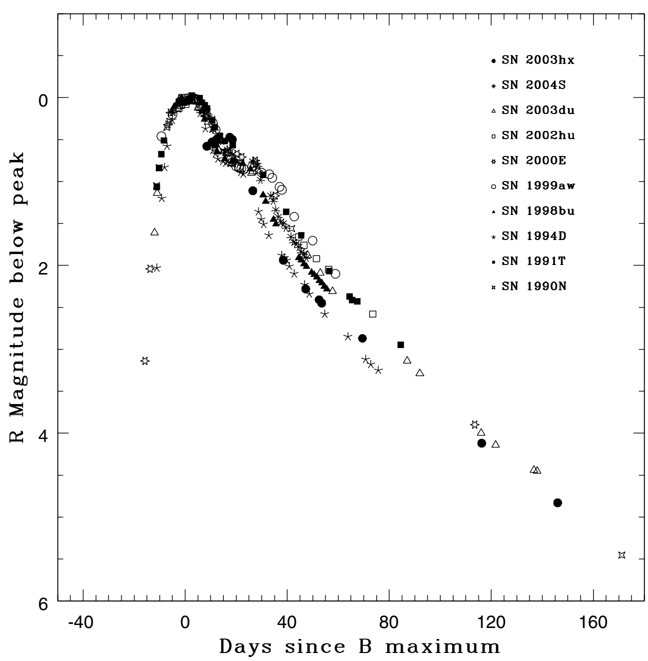

Figure 11. *R*-band light curve of SN 2003hx together with those of SN 2004S, SN 2003du, SN 2002hu, SN 2000E, SN 1999aw, SN 1998bu, SN 1994D, SN 1991T and SN 1990N. All the light curves are shifted to match the time of *B* maximum and peak magnitude in *R* band.

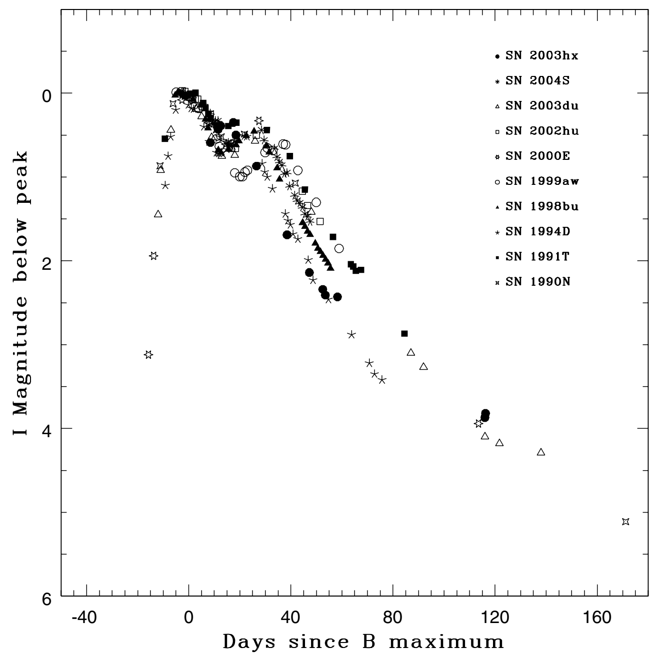

Figure 12. *I*-band light curve of SN 2003hx together with those of SN 2004S, SN 2003du, SN 2002hu, SN 2000E, SN 1999aw, SN 1998bu, SN 1994D, SN 1991T and SN 1990N. All the light curves are shifted to match the time of *B* maximum and peak magnitude in *I* band.

4 REDDENING ESTIMATE

The estimated reddening in the direction of SN 2003hx due to our own Galaxy from Schlegel et al. (1998) is $E(B-V) = 0.084$ mag. The supernova occurred very close to the nucleus of the galaxy NGC 2076, we therefore expect substantial reddening due to the host galaxy. The optical spectra demonstrates that SN 2003hx is a highly reddened supernova (refer Section 6). Fig. 13 shows the strong interstellar Na I D lines at the rest wavelength of the host galaxy and relatively weak absorption line due to the extinction in the Milky Way. The average equivalent width of the Galactic component of the Na I D absorption is 0.54 ± 0.11 Å, whereas the equivalent width of Na I D absorption due to the host galaxy is 5.02 ± 0.26 Å. Using the two relations between equivalent width of Na I D line and $E(B-V)$ (Turatto, Benetti & Cappellaro 2003) the measured equivalent width implies $E(B-V)$ as 0.09 and 0.28 for the Milky Way, the lower value being close to the estimate of Schlegel et al. (1998). The $E(B-V)$ values due to the host galaxy is estimated as 0.80 and 2.56. The sum of the lower values of $E(B-V)$ for Milky Way and host galaxy gives total reddening as 0.89. Further, we calculate $E(B-V)$ at the time of maximum using intrinsic colour at the epoch of maximum given by Nobili et al. (2003) which is listed in Table 4. We also estimate the total extinction following the photometric methods of Phillips et al. (1999) and the Lira's method (1995). However, the best estimate of reddening comes from a good measurement of Δm_{15} from where we deduce the intrinsic luminosity. This relationship between Δm_{15} and intrinsic luminosity is much more exhaustively tested than the extinction law. We obtain, using this method, our independent measure of R_v towards SN 2003hx. The value of R_v is listed is listed in Table 4. The values of total selective extinction obtained from different methods are listed in Table 4. Wang & Baade (2003) based on the spectropolarimetric observations inferred an equivalent width of 4.86 Å for the interstellar Na I D line, indicating significant dust extinction and a

Table 5. Absolute *B* magnitude at maximum, peak luminosity, $\Delta m_{15}(B)$ and ^{56}Ni masses of type Ia supernovae.

SN	Galaxy	M_B (mag)	$\Delta m_{15}(B)$ (mag)	log $L_{\rm bol}$ (erg s^{-1})	$M_{\rm Ni}$ M$_\odot$	Reference
1990N	NGC 4639		1.03			1
1991T	NGC 4527	−20.06	0.95 ± 0.05	43.36	1.14	2,3
1994D	NGC 4526	−18.95 ± 0.18	1.31 ± 0.08	42.91	0.41	2,4
1998bu	NGC 3368	−19.67 ± 0.20	1.01 ± 0.05	43.18	0.77	2,5
1999aw	Anonymous	−19.48 ± 0.11	0.81 ± 0.03	43.18	0.76	6
2000E	NGC 6951	−19.45	0.94 ± 0.05	43.29	0.90 ± 0.20	7
2002hu	MCG+6-6-12	−19.38 ± 0.30	1.00 ± 0.05	43.25 ± 0.07		8
2003du	UGC 9391	−19.34 ± 0.30	1.04 ± 0.04	43.14	0.88	9
2004S	MCG-05-16-021	−19.05 ± 0.23	1.26 ± 0.06	42.94	0.41	10
2003hx	NGC 2076	−19.20 ± 0.18	1.17 ± 0.12	43.01	0.66	11

References: (1) Lira et al. (1998), (2) Contardo et al. (2000), (3) Lira et al. (1998), (4) Richmond et al. (1995), (5) Suntzeff et al. (1999), (6) Strolger et al. (2002), (7) Valentini et al. (2003), (8) Sahu et al. (2006), (9) Anupama et al. (2005), (10) Misra et al. (2005), (11) this paper.

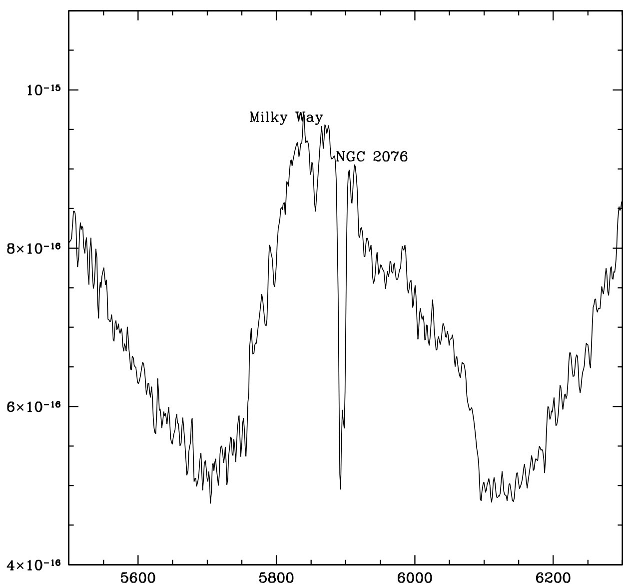

Figure 13. Spectra of SN 2003hx around Na I D absorption line. The two components due to the Milky Way and the host galaxy is clearly seen.

polarization of ∼2 per cent. If this polarization is due to dust in the host galaxy, it implies that the dust particles are smaller in size than their galactic counterparts. A similar conclusion about the dust particle size was arrived at by Sahu et al. (1998), in their study of dust property of the host galaxy NGC 2076. Our independent estimates of R_v also indicates the small size of dust particles as compared to their galactic counterparts. Wand & Baade (2003) based on these observations, found the ratio of total to selective extinction $R_v = A_v/E(B-V)$ to be 2.2. We adopt $E(B-V) = 0.56 \pm 0.23$ (using the value obtained from the relation between Δm_{15} and intrinsic luminosity) and $R_v = 1.97 \pm 0.54$ to estimate the total extinction in different filters, the values of which are listed in Table 4. We see that the reddening due to our own galaxy is very small in comparison to the total reddening. Thus, a large amount of extinction could arise in the host galaxy of SN 2003hx.

5 ABSOLUTE LUMINOSITY AND BOLOMETRIC LIGHT CURVE

Assuming $H_0 = 70$ km s^{-1} Mpc−1 and the radial velocity of NGC 2076 as $v_r = 2142 \pm 5$ km s^{-1}, we find a distance modulus of 32.456 mag. The total extinction estimated is mentioned in Table 4. From these the absolute magnitudes estimated in different bands are $M^B = -19.20 \pm 0.18, M^V = -19.22 \pm 0.15, M^R = -18.91 \pm 0.22$ and $M^I = -18.70 \pm 0.17$. Altavilla et al. (2004) suggest another method for estimating absolute magnitude using a relation between $M_{\rm max}$ and Δm_{15}. Adopting the values of linear fit coefficients as given by Altavilla et al. (2004) for $R_v = 2.2$, we obtain $M^B{}_{\rm max} = -19.38 \pm 0.10$. The values of the absolute magnitude in *B* band obtained by the above two methods are in good agreement with each other.

The bolometric light curve of SN 2003hx is estimated using the optical observations presented here. During the early phase most of the flux emerges in the optical from a type Ia supernova (Suntzeff 1996), thus the integrated flux in *UBVRI* bands gives a good estimate of the bolometric luminosity. The peak bolometric luminosity is directly related to the radioactive nickel ejected in the explosion. The dereddened magnitudes were converted to flux using calibrations by Fukugita, Shimasaku & Ichikawa (1995). Since we have very few *U*-band observations, we corrected for the missing passband flux in the optical for a contribution of 10 per cent as shown by Contardo, Leibundgut & Vacca (2000). Also, to construct the full *UVOIR* bolometric light curve we should combine the ultraviolet and the near-IR data with the optical data. Suntzeff (1996) constructed the full *UVOIR* bolometric light curve for SN 1992A by integrating the flux in wavelength range of 2000 Å to 2.2 μm. This shows that both the ultraviolet and the near-IR contribution is ∼10 per cent each of the total *UVOIR* luminosity for ∼80 d since the time of *B*-band maximum. Thus, a correction for the missing flux is required and has to be applied to the bolometric luminosity which is estimated using the optical data alone. We correct for a total contribution of 20 per cent from both ultraviolet and near-IR regions. In Fig. 14 we show the *UVOIR* bolometric light curve as dots. The dashed line in Fig. 14 shows the contribution derived from the *BVI* bands alone, as obtained from fitted templates from −5 to 80 d with reference to the time of *B*-band maximum. The *UVOIR* luminosity estimated indicates a peak luminosity of $\log L = 43.01$. The light curves are powered by radioactivity and the amount of ^{56}Ni mass ejected may be estimated using the peak luminosity (Arnett 1982). Assuming a rise time of ∼18 d for SN 2003hx and the peak *UBVRI* bolometric luminosity determined, the amount of ^{56}Ni is estimated to be $M_{\rm Ni} = 0.50$ M$_\odot$. Using the corrected bolometric luminosity, the ^{56}Ni mass estimate is 0.66 M$_\odot$.

We see that the peak bolometric luminosity and the ejected ^{56}Ni mass of SN 2003hx is comparable to that of SN 1998bu and SN

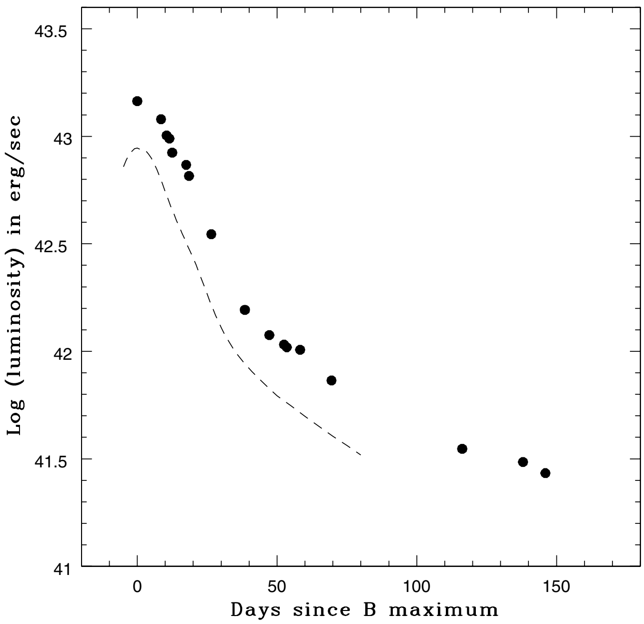

Figure 14. Bolometric light curve of SN 2003hx. The dots show the corrected *UVOIR* bolometric light curve and the dashed line shows the bolometric light curve constructed from the *BVI* fits of Hamuy et al. (1996).

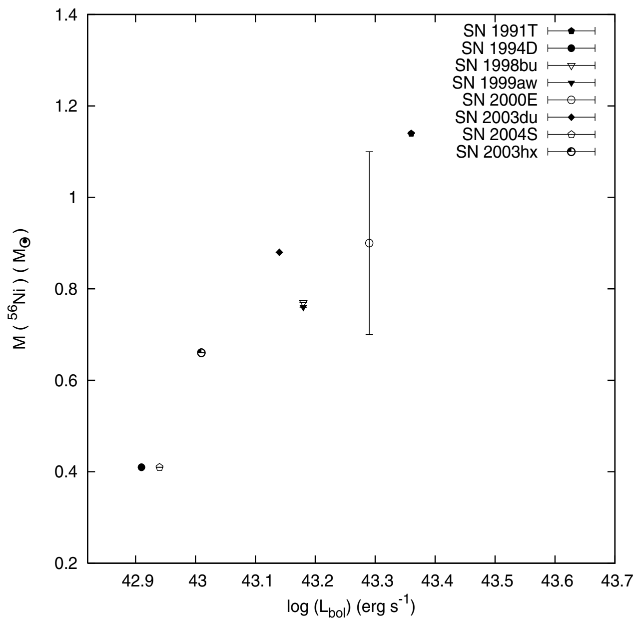

Figure 16. Comparison of peak bolometric luminosity and ejected ^{56}Ni mass of SN 2003hx with other type Ia supernovae.

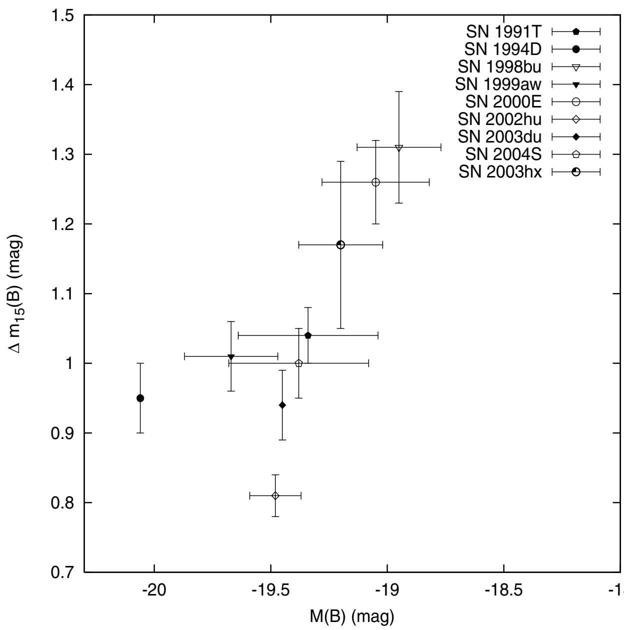

Figure 15. Comparison of maximum absolute B-band magnitudes and Δm_{15} of SN 2003hx with other type Ia supernovae.

1999aw though the amount of ^{56}Ni ejected in the other two cases is slightly higher than SN 2003hx. Table 5 lists the parameters of different type Ia supernovae including SN 2003hx. We present plots of two simple parameters: absolute magnitude versus Δm_{15} (Fig. 15) and log($L_{\rm bol}$) versus ^{56}Ni (Fig. 16). We see that M_B and Δm_{15} as well as log ($L_{\rm bol}$) and ^{56}Ni for type Ia supernovae follow a linear relation and the location of SN 2003hx in both these plots agrees well with the rest of the sample.

6 SPECTRAL EVOLUTION

Optical spectra of SN 2003hx were obtained on four different epochs during +10 to +53 d past the B maximum. Figs 17 and 18 show the spectral evolution of SN 2003hx. All the spectra show a deep absorption around 6100 Å due to Si II, indicating the supernova to be a normal type Ia event. The Na I D lines are clearly visible and strong, suggesting a high value of reddening, consistent with the estimates in Section 4.

A comparison of the spectra of SN 2003hx with those of other normal type Ia events, namely SN 2003cg (Elias-Rosa et al. 2006),

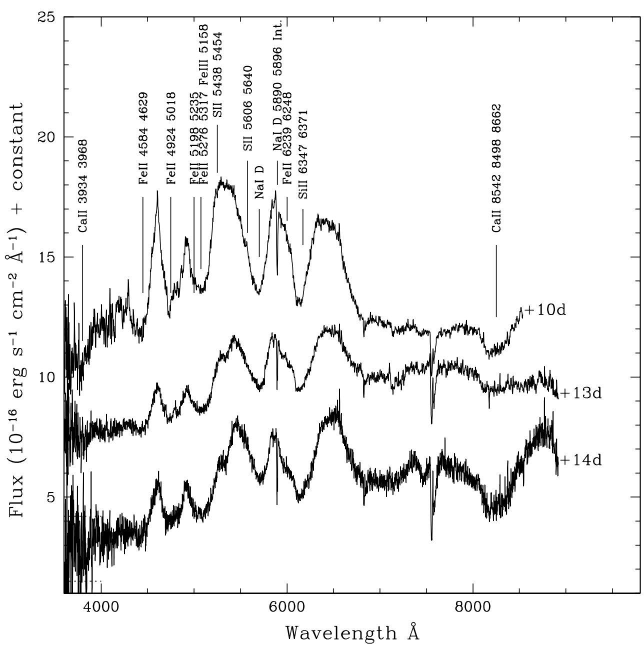

Figure 17. The spectrum of SN 2003hx on +10, +13 and +14 d past the B maximum.

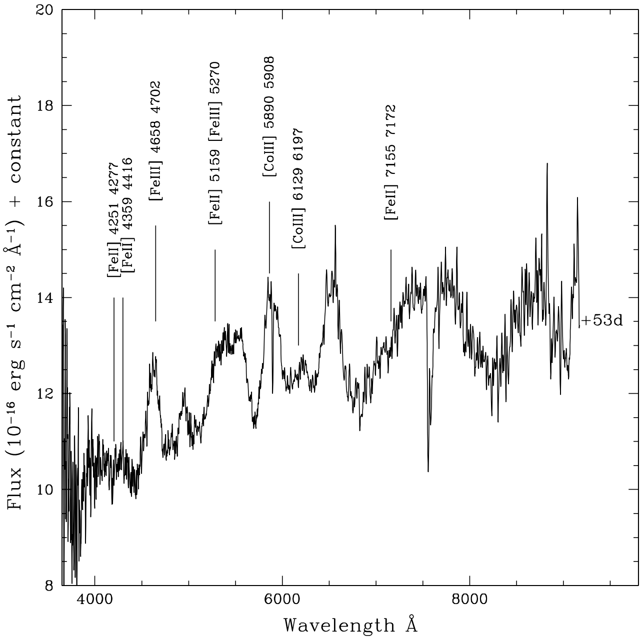

Figure 18. The spectrum of SN 2003hx +53 d past *B* maximum.

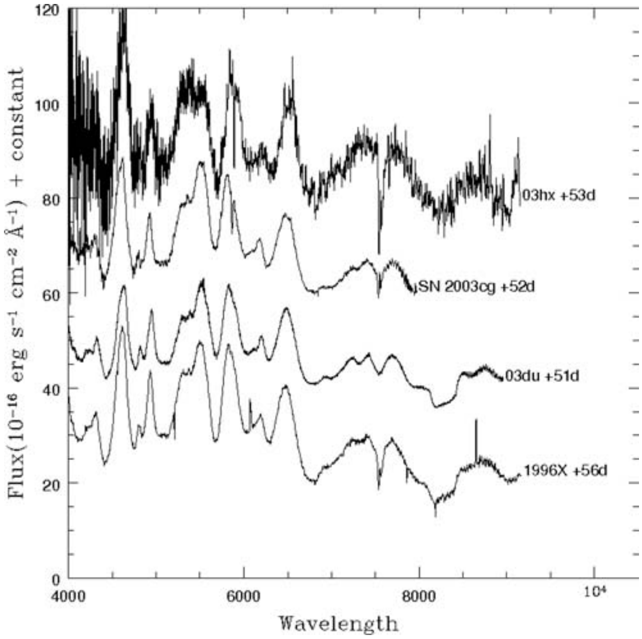

Figure 20. Comparison of the spectrum of SN 2003hx on day +53 with those of SN 2003du, SN 2003cg and SN 1996X at a similar epoch (see text for references).

SN 2003du (Anupama et al. 2005), and SN 1996X (Salvo et al. 2001) indicates an overall similarity in the spectra. However, there are a few discrepancies. The +13 d spectrum (Fig. 19 indicates very weak or no Ca II IR triplet in SN 2003hx, while it is present, but weak compared to the other SNe at later phases (Fig. 20). Further, the S II features at 5300–5600 Å appear to be stronger in SN 2003hx.

The expansion velocity is measured for the first three epochs, based on the absorption minimum of Si II 6355 Å line, and is found to be ∼10 400 km s^{-1}. As our spectroscopic coverage is rather sparse, not much can be inferred about the velocity evolution in SN 2003hx. However, as seen in Fig. 21, the velocity estimated for the first three epochs compares well with the estimates for other type Ia events, SN 2003cg (Elias-Rosa et al. 2006), SN 2003du (Anupama et al. 2005), SN 2002er (Kotak et al. 2005), SN 2002bo (Benetti et al. 2004), SN 1996X (Salvo et al. 2001) and SN 1994D (Patat et al. 1996).

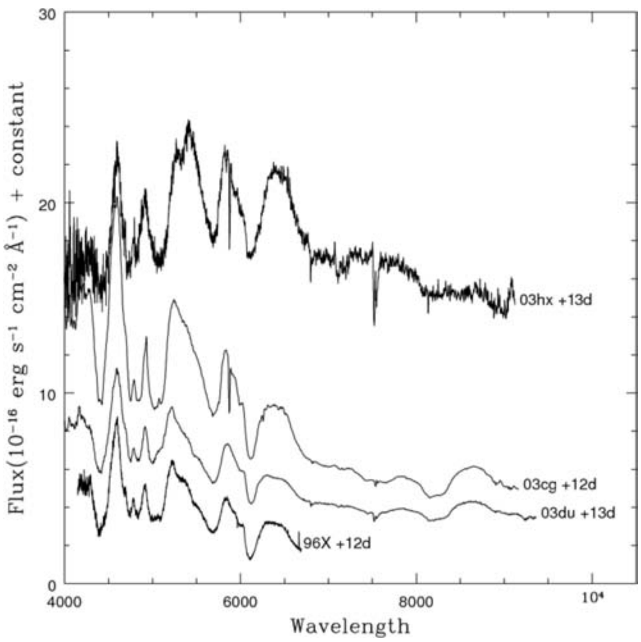

Figure 19. Comparison of the spectrum of SN 2003hx on day +13 with those of SN 2003du, SN 2003cg and SN 1996X at a similar epoch (see text for references).

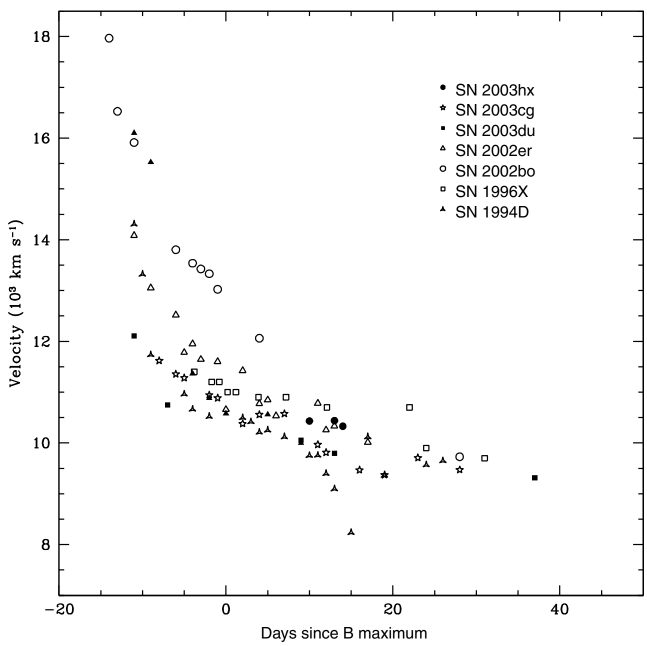

Figure 21. Expansion velocity derived from the absorption minima of Si II 6355 Å line for SN 2003hx, SN 2003cg, SN 2003du, SN 2002er, SN 2002bo, SN 1996X and SN 1994D (see text for references).

7 CONCLUSIONS

We present here the *UBVRI* photometric observations of SN 2003hx over a period of ∼146 d after *B* maximum obtained using the 2.01-m HCT. We also present the optical spectra of SN 2003hx at four epochs. We study the light curve evolution in *BVRI* bands and estimate the peak magnitudes and the time of maximum in different bands using the template fitting method. The light curve of SN 2003hx in the *B* band is approximated well with the template of SN 1992al whereas the *V* and *I* bands fit best with the template of SN 1992A. The light curve parameter $\Delta m_{15}(B)$ is estimated to be 1.17 ± 0.12 which shows SN 2003hx as a mid-decliner. The colours of SN 2003hx are quite close to the colour estimates of SN 1999aw whereas the light curve evolution matches very well with that of SN 1994D. Both SN 2003hx and SN 1994D occurred in lenticular galaxies. We infer from both photometric and spectroscopic studies that SN 2003hx is a highly reddened supernova with $E(B - V) = 0.56 \pm 0.23$. We estimate $R_v = 1.97 \pm 0.54$ which indicates the small size of dust particles as compared to their galactic counterparts. A comparison of the absolute magnitude $M_B = -19.20 \pm 0.18$ with that of other normal type Ia SNe shows that SN 2003hx is comparable in brightness to SN 1999aw. SN 2003hx matches well with the rest of the SNe Ia sample and shows a typical linear behaviour in M_B versus $\Delta m_{15}(B)$ relation. The bolometric light curve indicates the decay of total luminosity of the SNe. The peak bolometric luminosity $\log L = 43.01$ yields a value of ^{56}Ni mass ejected to be $0.66\,M_{\odot}$. Comparing the nickel masses ejected for different SNe (Table 5), we see that the ejected mass of ^{56}Ni for SN 2003hx is slightly the higher side. The spectral evolution indicates SN 2003hx to be a normal type Ia event.

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