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Multiband Optical Photometry and Bolometric Light Curve of the Type Ia Supernova 2004S

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ABSTRACT

We present BVR_cI_c broad band CCD photometry of the Type Ia supernova SN 2004S, which appeared in the galaxy MCG-05-16-021, obtained during 2004 February 12 to March 22. Multiband and bolometric light curves constructed using our data as well as other available data are presented. The time of B band maximum and the peak magnitudes in different bands are obtained using the fits of light curve and colour templates. We clearly see a strong shoulder in R_c band and a second maximum in I_c band. SN 2004S closely resembles SN 1992al after maximum. From the peak bolometric luminosity we estimate the ejected mass of ^{56}Ni to be 0.41 $M_\odot$.

Key words: supernovae: general - supernovae: individual: SN 2004S

1 INTRODUCTION

In recent years significant progress has been made in the study of Type Ia Supernovae (SNe), but many of their properties remain fairly uncertain. Supernovae of Type Ia are among the most luminous stellar outbursts and because of the homogeneity in their properties (Höflich et al. 1996) have been regarded as standardizable candles for determining extragalactic distances and deriving cosmological parameters. They are thought to be thermonuclear explosions of carbon-oxygen white dwarfs (Hoyle & Fowler 1960). However, Type Ia supernovae are suspected to be not a perfectly homogeneous group, from both their light curves and spectra (Pskovskii 1970, 1977; Barbon, Ciatti, & Rosino 1973; Barbon et al. 1990; Branch 1981; Elias et al. 1985; Frogel et al. 1987; Phillips et al. 1987; Cristiani et al. 1992). Some SNe have shown significant deviations such as SN 1991T (Filippenko et al. 1992a; Phillips et al. 1992; Jeffery et al. 1992; Mazzali et al. 1995) and SN 1991bg (Filippenko et al. 1992b; Leibundgut et al. 1993; Turatto et al. 1997; Mazzali et al. 1997). The classic Si II and Ca II lines were seen very late and with diminished strength in SN 1991T and its early spectrum was dominated by Fe III lines (Filippenko et al. 1992a; Ruiz-Lapuente et al. 1992) while the nebular phase was very similar to other SN Ia (Leibundgut et al. 1993). SN 1991bg was a strongly subluminous event which established the existence of a wide range of luminosities among Type Ia supernovae (Filippenko et al. 1992b; Leibundgut et al. 1993). SN 1991bg showed an absorption trough near 4000Åwhich was attributed to Ti II ($\lambda\lambda$ 4395Å, 4444Åand 4468Å) absorption (Filippenko et al. 1992b; Mazzali et al. 1997). Other supernovae showing remarkable deviations are SN 1999ac, a slow rise and fast decliner (Labbe et al. 2001; Phillips et al. 2003), SN 2000cx, a fast riser and slow decliner had unusually blue (B-V) colours $\sim$ 30 days after blue maximum (Li et al. 2001; Candia et al. 2003), while SN 1986G (Phillips et al. 1987) appeared to have properties between normal supernova and the extreme case of SN 1991bg. SN 1999by is a rare example of a "peculiar", fast declining SN Ia. Recently Garnavich et al. (2004) presented detailed photometric and spectroscopic observations of SN 1999by. It is one of the few SNe to show significant intrinsic polarization (Howell et al. 2001). Li et al. (2003) describe the even stranger SN 2002cx, which had premaximum spectra like 1991T, a luminosity like SN 1991bg (subluminous event), a slow late time decline and unidentified spectral lines. In spite of these differences in SNe Ia, they still seem to follow a few common patterns in their behavior (Leibundgut 2000). Of these, the correlation between the linear decline rate and luminosity is the best known (Phillips 1993). The template fitting or Δm_{15} (the number of magnitudes in B band by which the SN declines in the first 15 days after maximum) method (Hamuy et al. 1996a; Phillips et al. 1999), the multi-colour light curve shape correction (Riess et al. 1996, 1998), and the stretch factor (Perlmutter et al. 1997) exploit this property of SNe Ia to determine their luminosities.

In this paper, we report optical photometry of the Type Ia supernova SN 2004S. This supernova (mag 16 on red CCD images) was discovered on 2004 February 3.54 UT by Martin (2004) at Perth Observatory with the 0.61 - m Perth/Lowell Automated telescope in the course of the Perth Automated

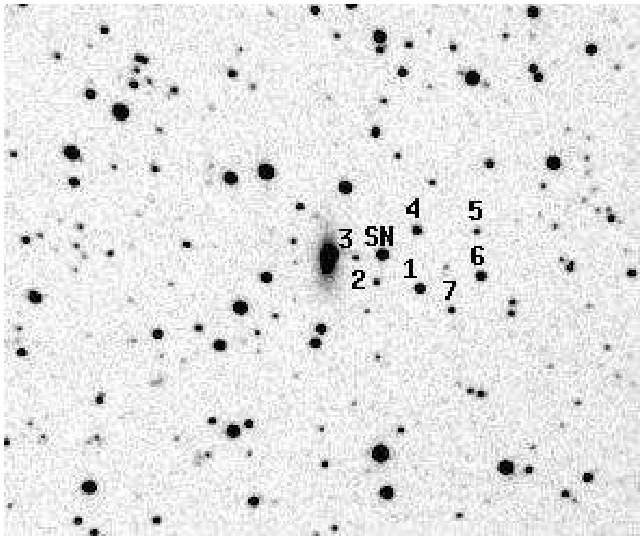

Figure 1. SN 2004S and the comparison stars.

Supernova Search. The position of the supernova was reported by Biggs (2004) to be R.A. = $06^{h}45^{m}43^{s}.50 \pm 0''.1$, Dec. = $-31^{\circ}13'52''.5 \pm 0''.1$ (J2000). The SN is situated $47''.2$ W and $2''.5$ S of the galaxy MCG-05-16-021. Spectrophotometry obtained at CTIO by Suntzeff et al. (2004) on February 6.1 UT identifies it as a type Ia supernova with an expansion velocity of $\sim$ 9300 km/sec.

We have carried out multi-colour optical photometric observations during the early decline phase. We have used these in combination with data available in the literature to study the development of the optical light curve. The details of the photometric observations are presented in the next section while the development of the light curve and other properties of the supernova are discussed in the sections to follow.

2 OBSERVATIONS AND DATA REDUCTION

We began optical photometry of SN 2004S approximately eight days after the discovery. The observations were carried out from ARIES, Nainital, India at 27 epochs during the period 2004 February 12 to March 22 using a 1024 $\times$ 1024 pixel^2 CCD camera attached to the f/13 Cassegrain focus of the 104-cm Sampurnanand Telescope. One pixel of the CCD chip corresponds to a square of $\sim$ 0.38 arcsec while the entire chip covers a field of 6 $\times$ 6 arcmin^2 on the sky. The gain and read out noise of the CCD camera are 12 electrons per Analogue to Digital Unit (ADU) and 7 electrons respectively. Due to its large negative declination the supernova had to be observed at a low elevation through large airmass. This precluded U band observations, but we were able to carry out photometry at BV$R_c I_c$ bands during most of the nights until March 22, beyond which it became too faint to follow. Exposure times in the early decline phase of the B,V, R_c and I_c band images were 300, 300, 120 and 120s respectively whereas the exposure time was increased considerably in the later phase so as to get a good signal. The exposure time in this phase varied from 10 min in R_c and I_c to 30 min in B and V bands. We observed several bias and

Table 1. Adopted BVRI magnitudes of comparison stars. Star Numbers correspond to those marked in figure 1.

Star No.	B	V	R	I
1	16.44	15.61	15.16	14.74
2	18.50	17.45	16.79	16.22
3	18.18	17.60	17.30	16.91
4	17.89	16.53	15.65	14.86
5	18.55	17.52	16.88	16.33
6	16.28	15.59	15.19	14.78
7	17.85	17.00	16.51	16.07

twilight flat frames with the CCD camera to calibrate the supernova images using standard techniques. Data reduction was carried out using IRAF[1] and MIDAS softwares. The images were bias corrected and flat fielded using the CCD reduction package in IRAF. For photometric calibrations we have used comparison stars 1, 2, 4, 5, 6 and 7 of Krisciunas (2004a). The standard magnitudes for the local calibrators as determined by Krisciunas (2004a) are given in Table 1 corresponding to the stars marked in the finder chart in Figure 1. The calibration stars were observed along with SN 2004S. The instrumental magnitudes of SN 2004S and the comparison stars were estimated using aperture photometry in IRAF. We determined the zeropoints for our system on each observing night by matching the instrumental magnitudes to the values given in Table 1 to obtain the standard magnitude of the SN. The difference in the measured (B_{obs}, V_{obs}, $R_{c_{obs}}$ and $I_{c_{obs}}$) and standard (B_{st}, V_{st}, $R_{c_{st}}$ and $I_{c_{st}}$) BV$R_c I_c$ magnitudes of calibration star 1 is plotted in Figure 2. We see that the difference is consistent with zero, with standard deviations 0.02, 0.04, 0.05 and 0.06 mag in B, V, R_c and I_c passbands respectively. These standard deviations were added in quadrature to the instrumental errors in order to get the final estimates of error in the determined magnitudes in different bands. The resulting BV$R_c I_c$ magnitudes of SN 2004S based on our observations are provided in Table 2 along with errors.

3 UBV$R_C I_C$ LIGHT CURVES AND COLOR CURVES

Our observations started several days after the discovery so we do not have observations near peak brightness. To estimate the peak magnitude and the peak time in different bands by making template fits it is important to have observations temporally as close to the peak as possible. Late time observations are also important to perform template fitting of the SN light curves. For this purpose, we have used observations of SN 2004S reported elsewhere. This also allows us to cross compare our photometry with other available data in the literature. The U band observations taken from the literature help us determine the total luminosity at selected epochs and hence construct the bolometric light curve. Our observations present a temporally dense coverage. The frequency distribution of our data is N(B, V, R_c, I_c) = (20, 25, 25, 25). The

[1] IRAF is distributed by the National Optical Astronomy Observatory, USA.

Table 2. BVR_c and I_c magnitudes of SN 2004S along with errors, Julian date and mid UT of observations are listed.

Date (UT)	Time in JD	B (mag)	V (mag)	R_c (mag)	I_c (mag)
2004 02 12.614	2453048.1141	14.85 ± 0.022	14.58 ± 0.041	14.52 ± 0.051	14.76 ± 0.062
2004 02 13.608	2453049.1088	–	14.75 ± 0.043	–	14.88 ± 0.061
2004 02 14.632	2453050.1328	15.17 ± 0.022	14.75 ± 0.042	14.64 ± 0.051	14.85 ± 0.063
2004 02 15.677	2453051.1773	–	–	14.77 ± 0.052	14.85 ± 0.061
2004 02 18.601	2453054.1011	15.48 ± 0.022	14.91 ± 0.041	14.91 ± 0.050	15.12 ± 0.061
2004 02 19.605	2453055.1055	15.71 ± 0.023	14.98 ± 0.040	15.04 ± 0.051	15.11 ± 0.061
2004 02 20.607	2453056.1070	15.76 ± 0.022	15.01 ± 0.040	15.01 ± 0.050	15.14 ± 0.061
2004 02 21.592	2453057.0920	15.88 ± 0.022	15.07 ± 0.040	15.00 ± 0.052	15.15 ± 0.061
2004 02 22.632	2453058.1327	16.00 ± 0.022	15.13 ± 0.040	15.07 ± 0.050	15.10 ± 0.061
2004 03 01.618	2453066.1185	–	15.53 ± 0.042	15.15 ± 0.051	–
2004 03 03.587	2453068.0885	–	15.56 ± 0.041	15.20 ± 0.050	14.96 ± 0.061
2004 03 04.612	2453069.1134	–	15.78 ± 0.042	15.37 ± 0.051	15.08 ± 0.061
2004 03 08.591	2453073.0913	–	15.99 ± 0.049	15.56 ± 0.066	15.18 ± 0.067
2004 03 09.580	2453074.0823	17.23 ± 0.033	16.02 ± 0.041	15.62 ± 0.051	15.28 ± 0.061
2004 03 10.579	2453075.0814	17.31 ± 0.026	16.11 ± 0.041	15.73 ± 0.051	15.34 ± 0.062
2004 03 11.600	2453076.1041	17.32 ± 0.028	16.13 ± 0.042	15.81 ± 0.052	15.38 ± 0.064
2004 03 12.597	2453077.1011	17.41 ± 0.030	16.20 ± 0.041	15.87 ± 0.051	15.48 ± 0.061
2004 03 13.611	2453078.1154	17.47 ± 0.029	16.25 ± 0.041	15.89 ± 0.051	15.47 ± 0.061
2004 03 14.614	2453079.1182	17.58 ± 0.028	16.30 ± 0.042	15.94 ± 0.051	15.63 ± 0.062
2004 03 16.602	2453081.1069	17.59 ± 0.038	16.41 ± 0.044	16.05 ± 0.052	15.74 ± 0.062
2004 03 17.615	2453082.1200	17.62 ± 0.028	16.43 ± 0.041	16.11 ± 0.051	15.80 ± 0.061
2004 03 18.598	2453083.1024	17.63 ± 0.027	16.43 ± 0.041	16.13 ± 0.051	15.83 ± 0.061
2004 03 19.594	2453084.0988	17.66 ± 0.030	16.51 ± 0.041	16.17 ± 0.051	15.88 ± 0.062
2004 03 20.597	2453085.1018	17.73 ± 0.031	16.52 ± 0.043	16.23 ± 0.052	15.96 ± 0.062
2004 03 21.614	2453086.1184	17.74 ± 0.028	16.56 ± 0.041	16.25 ± 0.051	15.99 ± 0.061
2004 03 22.615	2453087.1193	17.74 ± 0.030	16.56 ± 0.042	16.30 ± 0.051	16.05 ± 0.062

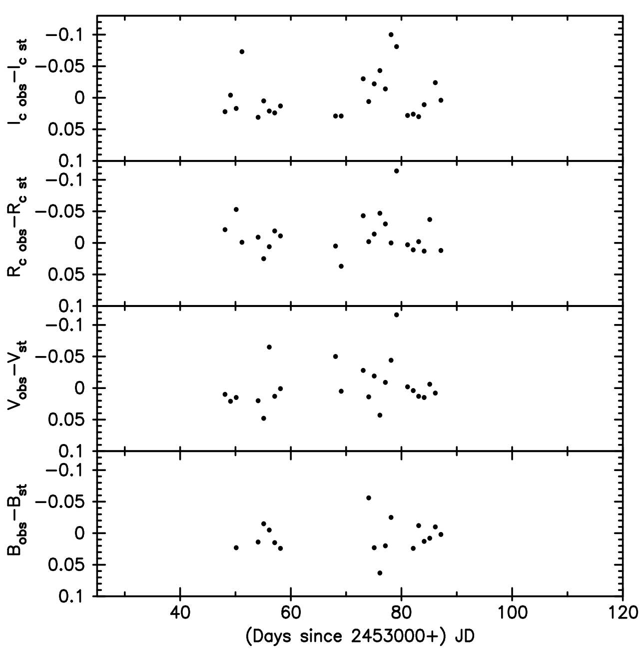

Figure 2. Scatter in the estimated magnitude of calibration star 1 during multiple observing nights.

other observations have been taken from compilations at http://www.astrosurf.com/snweb2/2004/04S_/04S_Meas.htm with contributions from Krisciunas (2004b), Espinoza (2004), Santallo (2004) and Lacruz (2004). The frequency distribution of the data taken from the literature is N(U, B, V, R_c, I_c) = (18, 20, 20, 23, 20). The BVR_cI_c light curves are shown in Figure 3. U band data taken from the literature are also included for comparison. To determine the value of χ^2 in template fitting we have assumed an error of 0.05 mag in all the data points available in the literature.

Since we do not have observations around peak brightness we adopted the template fitting method to get the magnitudes at peak. We attempted to fit the different template sets given by Riess et al. (1996) and Hamuy et al. (1996b). Hamuy et al. (1996b) present a family of six BVI templates produced from CCD photometry of seven well-observed events (1992bc, 1991T, 1992al, 1992A, 1992bo, 1993H and 1991bg). These templates were fit to our observed data using a χ^2 minimizing technique which solved simultaneously for the epoch of maximum brightness in blue band $t_{B_{max}}$ and the magnitudes $B(t_{B_{max}})$, $V(t_{B_{max}})$ and $I_c(t_{B_{max}})$. We refer to these magnitudes as $B(t_{B_{max}})$, $V(t_{B_{max}})$ and $I_c(t_{B_{max}})$ in the paper. One set of BVI templates from Hamuy et al. (1996b), that for SN 1992al, provided a much better fit, as judged by the value of the reduced χ^2, than all others. We also found that the SN 1992al template (Hamuy et al. 1996b) fit our data better than the parametrized multiband templates given by Riess et al. (1996). The time for B_{max} obtained using templates given by Riess et al. (1996) was two days later than that obtained from Hamuy et al. (1996b) templates. The similarity in behavior between SN 2004S and SN 1992al is remarkable. Even in I_c band, where the difference between SN Ia are more pronounced (Suntzeff 1996), SN 2004S follows SN 1992al very closely.

Since the complete data set includes data from different telescopes and different filter systems in different instruments there can be systematic differences in the estimated magnitudes (Suntzeff 2000). For example, Stritzinger et al. (2002) find systematic difference of 0.05 mag in photometry by two different telescopes (CTIO and YALO), even though the photometry is reduced to the same local standards. A method called "S-correction", to bring photometry to a standard system, in such cases was suggested by Stritzinger et al. (2002). Krisciunas et al. (2003) and Krisciunas et al. (2004c) have applied these corrections to photometry of various SNe obtained using CTIO 0.9m and YALO telescopes. To assess any such systematic differences between our data set and that from literature, we made B, V, I template fits, discussed above, to these data sets independently. We found no systematic difference in B band magnitudes of the two sets. However, our V magnitudes are fainter by 0.03 mag and I_c magnitudes are brighter by 0.05 mag compared to the literature data set. These differences are comparable to our observational errors. Hence, we do not find it necessary to apply S - correction to our data set while fitting templates to the combined data.

In Figure 3 we have included the BVI_c template fits to the data. The main parameters of SN 2004S as estimated from template fits are listed in Table 4. For a typical SN Ia a two day difference is seen between the times of B and V maximum (Leibundgut 1988). According to the best fit template, SN 2004S would have reached maximum brightness in I_c band slightly earlier than in B band and roughly two days later in V band.

Since our observations started ∼ 8 days after the peak in the B band, we do not have observations at or around the epoch of B band maximum. An excellent match of the SN 1992al light curve shape with that of SN 2004S indicates that the peak in B band occurred at JD 2453039.42. Though individual SNe can be different in their light curve shapes, it seems unlikely that the peak magnitudes $B(t_{B_{max}})$, $V(t_{B_{max}})$ and $I_c(t_{B_{max}})$ of SN 2004S as inferred from the overall match of light curves with those of SN 1992al would be much in error. As a consistency check, we compare the colours of SN 2004S at this epoch with those obtained using the intrinsic colour curves of SN Ia population given by Nobili et al. (2003).

Nobili et al. (2003) present the intrinsic colour curves for a sample of 48 well observed nearby SN Ia for 40 days from the epoch of B_{max}. We estimate total selective extinction along the line of sight towards SN 2004S comparing the observed colours with the intrinsic colour curves given by Nobili et al. (2003). Corresponding selective extinctions were taken as fit parameters. Best fit values of total selective extinctions thus obtained are listed in Column 2 of Table 3. The shapes of observed colour curves are similar to the intrinsic colour curves given by Nobili et al. (2003) except for systematic shifts in individual colour curves due to selective extinction. In Figure 4, observed colour curves are plotted over intrinsic colour curves, corrected for the best fit values of selective extinction.

Independently, light curve template fitting gives $B(t_{B_{max}})$, $V(t_{B_{max}})$ and $I_c(t_{B_{max}})$. From these we calculate another set of $E(B-V), E(B-I_c), E(V-I_c)$ using intrinsic colours at $t_{B_{max}}$ (Nobili et al. 2003). These values are listed in Column 3 of Table 3. Comparison of the two sets of selective extinction values shows that the observed colours at $t_{B_{max}}$ are consistent with the intrinsic colours given by Nobili et al. (2003). We find that these values are also consistent with the fitted values in Column 2 of Table 3.

Table 3. Selective extinction along the line of sight towards SN 2004S. Column 2 are the values obtained as a fit to the observed and intrinsic colours. Column 3 are the values at $t(B_{max})$ obtained from the best fit template, intrinsic colours and galactic extinction law $R_v = 3.1$. Column 4 are the values obtained using best fit E(B−V) from colour curves and galactic extinction law $R_v = 3.1$.

	from fits to colour curves	at $t(B_{max})$: template fits	galactic extinction law
E(B−V)	0.18 ± 0.054	0.20 ± 0.095	0.18 ± 0.054
$E(B-I_c)$	0.34 ± 0.068	0.47 ± 0.112	0.40 ± 0.122
$E(V-R_c)$	0.08 ± 0.068		0.10 ± 0.031
$E(V-I_c)$	0.17 ± 0.073	0.27 ± 0.122	0.22 ± 0.069
$E(R_c-I_c)$	0.09 ± 0.076		0.12 ± 0.037

We next calculate the amount of selective extinction expected from galactic extinction law, all along the line of sight towards SN 2004S. Using $R_v = 3.1$ and $E(B-V) = 0.18 \pm 0.054$ mag, as obtained from fits to colour curves, values of selective extinctions in other colours are calculated and listed in Column 4 of Table 3. We find that these values are consistent, within errors, with those obtained from the colour curve fits listed as Column 2 of Table 3. The estimated reddening in this direction due to our own galaxy from Schlegel et al. (1998) is E(B-V) = 0.101 mag. So a small amount of extinction could arise in the host galaxy of SN 2004S.

Thus, we conclude that the magnitudes at $t_{B_{max}}$ as obtained using the templates of SN 1992al are fairly representative of the sample SN Ia of Hamuy et al. (1996b). Further, we use these magnitudes to calculate the peak luminosity of SN 2004S in § 4.

Hamuy et al. (1996b) do not present R_c band templates. In order to compare our R_c band light curve we construct an expected light curve using $(V-R_c)$ intrinsic colours (Nobili et al. 2003) and the V band template of SN 1992al (Hamuy et al. 1996b). We use for selective extinction, $E(V-R_c)$ listed in Column 2 of Table 3. This derived light curve is plotted in Figure 3.

As seen in Figure 3, except for a shoulder ∼ 26 days after $B(t_{B_{max}})$, the derived R_c band light curve represents the observed data well.

Also seen in Figure 3, is a pronounced second maximum in I_c band displayed by SN 2004S. This second maximum is reached nearly 26 days after the B maximum. The magnitude of the second I_c maximum is given in Table 4. Such behavior has also been noted for some other SNe Ia (Ford et al. 1993; Suntzeff 1996; Lira et al. 1998; Meikle 2000; Elias et al. 1981, 1985; Li et al. 2001). The second maxima in the I_c band light curves are usually attributed to a temporary increase in absorption which reduces with the fall in the degree of ionization several weeks after maximum light (Elias et al. 1981; Pinto & Eastman 2000).

We estimated the characteristic parameter Δm_{15}, the number of magnitudes in B band by which the SN declines in the first 15 days after maximum. The fitted template has a Δm_{15} of 1.11. We also calculated Δm_{15} by taking the

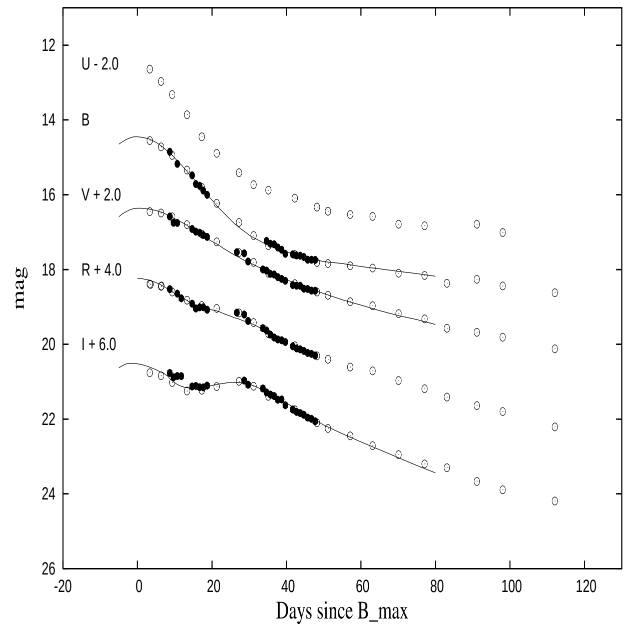

Figure 3. $UBVR_cI_c$ light curve of SN 2004S. The light curves are offset by a constant value on the magnitude scale as indicated in the plot. Filled circles represent our data and open circles represent data from Krisciunas (2004b). Uncertainties in the data are smaller than the size of the points.

B band peak magnitude obtained by the template fit and the observed B band magnitude after $\sim$ 15 days of the B band peak. This gives a value of $\Delta m_{15} = 1.26 \pm 0.061$. We estimated the average decline rate in all bands from our observations, using a time baseline of 10 days starting $\sim$ 8 days after the B band peak, when our observations began. These decline rates are listed in Table 4.

4 ABSOLUTE LUMINOSITY AND BOLOMETRIC LIGHT CURVE

Assuming H_0=65 km sec^{-1} Mpc^{-1} and the radial velocity of MCG-05-16-021 corrected for Local Group infall onto Virgo as v_r = 2516 km sec^{-1} as listed in LEDA (http://leda.univ-lyon1.fr/), we find a distance modulus of 32.94 mag. The total extinction estimated using the intrinsic colour curves of Nobili et al. (2003) are mentioned in table 3 (column 2). From these, the absolute magnitudes estimated at the time of $B(t_{B_{max}})$ in different bands are $M_B^{t_{B_{max}}} = -19.05 \pm 0.23$, $M_V^{t_{B_{max}}} = -18.96 \pm 0.18$, $M_{R_c}^{t_{B_{max}}} = -18.82 \pm 0.15$ and $M_{I_c}^{t_{B_{max}}} = -18.58 \pm 0.14$. Altavilla et al. (2004) suggests another method for estimating absolute magnitude using a relation between M^{max} and Δm_{15}. Adopting the values of linear fit coefficients of -19.61 ± 0.04 and 1.10 ± 0.15 as given by Altavilla et al. (2004), we obtain $M^B_{max} = -19.43 \pm 0.08$. The M_B^{max} values obtained by the above two methods are in good agreement with each other.

Since most of the flux from an SN Ia emerges in optical bands during the first few weeks (Suntzeff 1996), the integrated flux in $UBVR_cI_c$ bands provides a meaningful estimate of the bolometric luminosity, which is directly related to the amount of radioactive nickel synthesized

Table 4. Parameters of SN 2004S

Discovery Date	2004 February 3.54 UT
Host Galaxy	MCG-05-16-021
Galaxy Type	Morphological type S
RA (2000)	$06^h45^m43^s.5 \pm 0''.1$
Dec (2000)	$-31°13'52''.5 \pm 0''.1$
Offset from the nucleus	$47'.2$ W & $2''.5$ S
Spectrum	Type Ia
Radial velocity from galaxy redshift (km s^{-1})	2731 $\pm$ 36 2730 $\pm$ 42 (LEDA)
Radial velocity corrected for LG infall onto Virgo (km s^{-1})	2516 (LEDA)
Expansion velocity of the SN	9300 km sec^{-1}
Distance modulus (H_0=65 km s^{-1} Mpc^{-1})	μ = 32.94 mag
Time of B maximum (JD) (from template fitting)	2453039.42 $\pm$ 0.64
Magnitudes at $t_{B_{max}}$	$B(t_{B_{max}}) = 14.45 \pm 0.05$ $V(t_{B_{max}}) = 14.36 \pm 0.07$ $R_c(t_{B_{max}}) = 14.39 \pm 0.07$ $I_c(t_{B_{max}}) = 14.52 \pm 0.09$
Absolute Magnitudes at $t_{B_{max}}$	$M^B_{t_{B_{max}}} = -19.05 \pm 0.23$ $M^V_{t_{B_{max}}} = -18.96 \pm 0.18$ $M^{R_c}_{t_{B_{max}}} = -18.82 \pm 0.15$ $M^{I_c}_{t_{B_{max}}} = -18.58 \pm 0.14$
Adopted Total Extinction	$A_B = 0.716 \pm 0.220$ $A_V = 0.542 \pm 0.167$ $A_{R_c} = 0.439 \pm 0.135$ $A_{I_c} = 0.320 \pm 0.098$
Magnitude of secondary I_c maximum (from template)	15.020
Δm_{15} in B from template	1.11
Δm_{15} in B from observations	1.26 $\pm$ 0.061
Decline rate per day $\sim$ 8 days after $t_{B_{max}}$	B band 0.115 $\pm$ 0.029 V band 0.054 $\pm$ 0.014 R_c band 0.055 $\pm$ 0.035 I_c band 0.034 $\pm$ 0.048

and ejected in the explosion. Supplementing our data in BVR_cI_c bands and with U band observations reported by Krisciunas (2004b), we construct a bolometric light curve using de-reddened magnitudes and the estimated distance modulus till $\sim$ 40 days after $t_{B_{max}}$. The first U band observation was 3.105 days after $t_{B_{max}}$. To estimate the contribution of U band at peak we assumed that the (U-B) colour remains constant from the peak to 3.105 days. The magnitudes obtained were converted to flux using calibrations by Fukugita et al. (1995). The contribution from the U band at $t_{B_{max}}$ is $\sim$ 18.24 % and that from the I_c band is $\sim$ 11.12%. We have not accounted for the contribution from JHK bands. In Figure 5 we show the UVOIR bolometric light curve as a solid line from 0 to 40 days after $t_{B_{max}}$. The dash-dotted line in Figure 5 shows the contribution derived from the BVI bands alone, as obtained from fitted templates from -5 to 80 days with reference to $t_{B_{max}}$. We derive a peak bolometric luminosity of L = 8.715 x 10^{42} erg sec^{-1}. The bolometric peak is

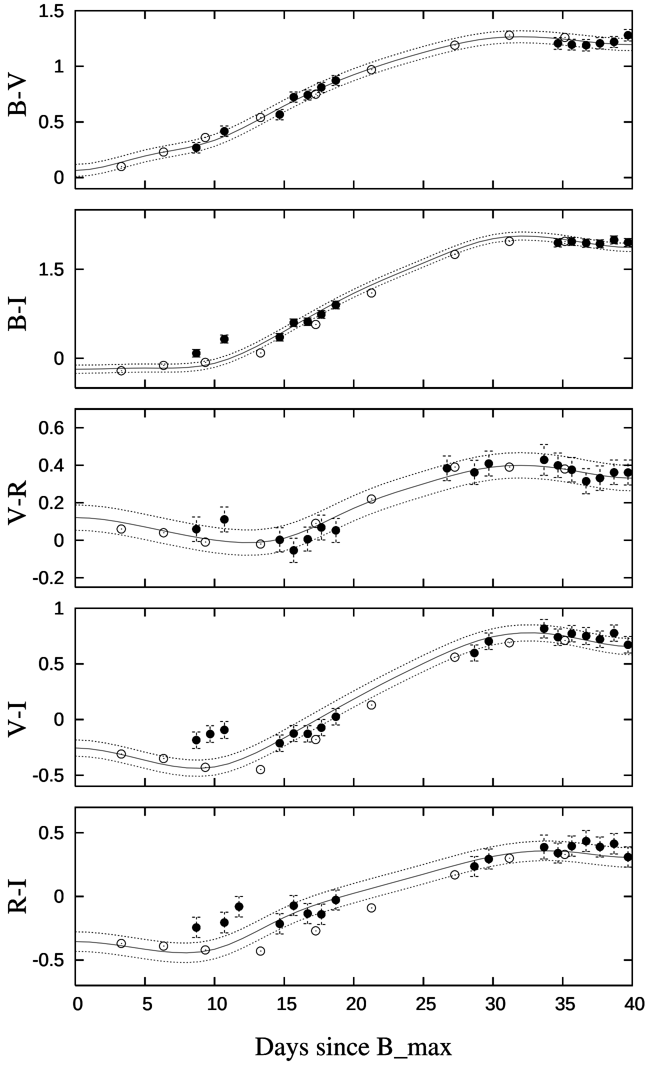

Figure 4. Color curves of SN 2004S. The middle (solid) line in each panel shows the extinction corrected colour curve bounded by errors (dashed lines) on both sides. Filled circles represent colours obtained from our observations, and open circles are from observations reported by others.

coincident in time with the B band peak within errors. We use the peak bolometric luminosity to derive ^{56}Ni mass using the method outlined by Branch (1992). It is understood that radioactivity powers the light curve and near the time of maximum light most of the energy released by the radioactivity is still being trapped and thermalized. The peak radiated luminosity is expected to be comparable to the instantaneous rate of energy release by radioactivity (Branch 1992). The peak luminosity can be expressed as

$$L = \alpha R(t_R) M_{Ni}$$

where α is a model dependent parameter expected to be of order unity, R is the radioactivity luminosity per unit nickel mass, evaluated at the time of maximum light t_R (the rise time) and M_{Ni} is the synthesized mass of ^{56}Ni. The B band rise time (t_R) is related to the post peak B band decline rate (β) in mag per 100 days as t_R=13+0.7β. In the case of SN 2004S $\beta = 8.45$, which gives a rise time of 18.915 days.

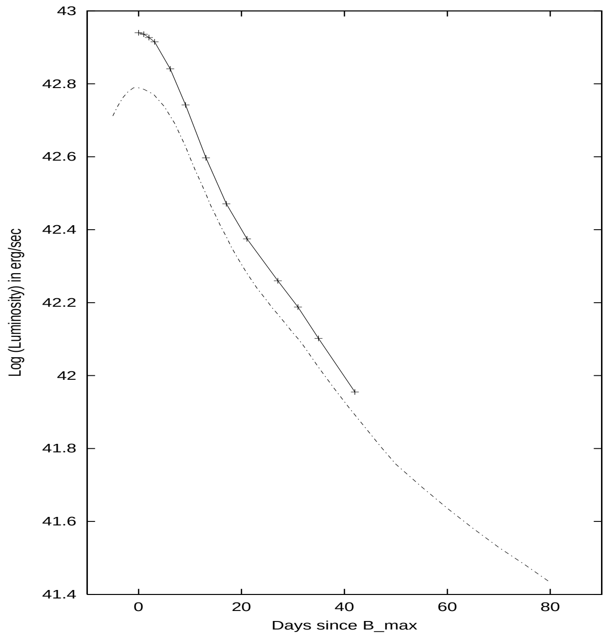

Figure 5. Bolometric light curve for SN 2004S. The solid line shows the Bolometric light curve constructed from $UBVR_cI_c$ bands and the dash-dotted line shows the bolometric light curve derived from BVI fits of Hamuy et al. (1996b).

For this value of t_R, R(t_R) works out to be 2.108 x 10^{43} erg $sec^{-1} M_{\odot}^{-1}$. The peak bolometric luminosity determined above then yields M_{Ni} = 0.41 $M_{\odot}$ for an assumed $\alpha = 1$.

Contardo et al. (2000) have calculated the bolometric luminosity and the ejected nickel mass for several SN Ia from UBVRI bolometric peak fluxes. In Table 5 we compare M^B_{max}, Δm_{15}, the peak bolometric luminosity and derived M_{Ni} for SN 2004S with corresponding values for the sample of Contardo et al. (2000) and two other recent SNe Ia: 1998bu (Hernandez et al. 2000; Leibundgut 2000) and 1999aw (Strolger et al. 2002). We find that SN 2004S represents a mid range value for M_{Ni}, similar to SN 1992A, SN 1992bo and SN 1994D. The subluminous event SN 1991bg is a fast decliner having a smaller value of Nickel mass ejected. SN 1991T, a peculiar and intrinsically bright supernova, has the largest value of derived M_{Ni} in the table. More recently, observations of cepheids by HST has revised the distance to NGC 4527, the host galaxy of SN 1991T (Gibson & Stetson 2001). Also, possible JHK maxima of this supernova have been determined by Krisciunas et al. (2004c). These measurements indicate that SN 1991T was only slightly overluminous, comparable to Type Ia SNe with similar values of Δm_{15}. Candia et al. (2003) point out another peculiar case of SN 2000cx as an underluminous event. Candia et al. (2003) have compared the bolometric light curves of SN 2000cx with SN 1999ee and SN 2001el. All three SN have similar Δm_{15}, 0.93, 0.94 and 1.13 respectively. However, Candia et al. (2003) also note that the underluminous nature of SN 2000cx requires further confirmation with a better distance estimate to the host NGC 524.

Table 6. Comparison of the properties of SN 2004S with SN 1992al. Decline rate, apparent magnitudes corrected for galactic extinction, Color and Absolute magnitudes at the time of B band maximum are compared for SN 1992al and SN 2004S. The numbers in parenthesis are the errors in the respective parameters.

SN	Δm_{15}	B_{max}	V_{max}	I_{max}	B_{max}-V_{max}	M_B^{max}	M_V^{max}	$M_{I_c}^{max}$
1992al	1.11(0.05)	14.60(0.07)	14.65(0.06)	14.94(0.06)	-0.05(0.03)	-19.47(0.32)	-19.42(0.31)	-19.13(0.31)
2004S	1.262(0.061)	14.04(0.05)	14.05(0.07)	14.34(0.09)	-0.01(0.08)	-19.05(0.23)	-18.96(0.18)	-18.58(0.14)

Table 5. Absolute B magnitude at peak, Peak Luminosity, Δm_{15} and ^{56}Ni masses of few SN Ia

SN	M_B (mag)	Δm_{15}	log L_{bol} (erg sec^{-1})	M_{Ni} $M_\odot$
1989B	-19.37	1.20	43.06	0.57
1991T	-20.06	0.97	43.23	0.84
1991bg	-16.78	1.85	42.32	0.11
1992A	-18.80	1.33	42.88	0.39
1992bc	-19.72	0.87	43.22	0.84
1992bo	-18.89	1.73	42.91	0.41
1994D	-18.91	1.46	42.91	0.41
1994ae	-19.24	0.95	43.04	0.55
1995D	-19.66	0.98	43.19	0.77
1998bu	-19.35	1.09	43.18	0.77
1999aw	-19.45	0.81	43.18	0.76
2004S	**-19.05**	**1.26**	**42.94**	**0.41**

5 COMPARISON WITH SN 1992AL

As mentioned in section 3 the template of SN 1992al fits best with our data set. We therefore compare the observed and derived properties of these two supernovae in Table 6. For SN 1992al de-reddened and K-corrected apparent magnitudes, colour, decline rate and absolute magnitudes are taken from Hamuy et al. (1996a). The corresponding quantities for SN 2004S are from this work. As we see from the table, the intrinsic properties of these two supernovae are very similar, although SN 2004S may be marginally less luminous particularly in the I_c band. The above comparison reinforces the general conclusion that for SNe Ia with similar light curves the intrinsic luminosities tend to be very similar.

6 CONCLUSIONS

We report photometric observations of SN 2004S which were carried out using the 1-m Sampurnanand Telescope at ARIES, Nainital during 2004 February 12 to March 22. $UBVR_cI_c$ light curves have been studied by combining our data with data available in the literature. We estimate the peak magnitudes in different bands and time of B maximum using the template fitting method. The light curve parameter Δm_{15} is estimated to be 1.26 $\pm$ 0.061 from our data. The light curve template of SN 1992al fits quite well to SN 2004S. We present the bolometric light curve which illustrates the decay of total luminosity of the supernova. The estimated peak luminosity 8.715 x 10^{42} erg/sec yields a value of ^{56}Ni mass ejected to be 0.41 $M_\odot$. Comparing the derived mass of ejected ^{56}Ni in different SNe Ia including SN 2004S we notice that for a given nickel mass, there could be a significant dispersion in peak luminosity, as the envelope structure and hence the decline rate parameter Δm_{15} could be different in different cases. SN 2004S can be placed as a mid-range decliner and the ejected mass of ^{56}Ni also has a mid-range value in this case.

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