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

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ABSTRACT

We present BVRcIc 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 Rc band and a second maximum in Ic 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. 1999) 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. Fskovski 1970, 1977. Barbon, Ciatti, & Rosino 1973. Barbon et al. 1994. Branch 1984. Elias et al. 1984. Frogel et al. 1987. Phillips et al. 1987. Cristiani et al. 1993. Some SNe have shown significant deviations such as SN 1991T (Filippenko et al. 1992b, Phillips et al. 1992a, Jeffery et al. 1992, Mazzali et al. 1993) 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. 1992, 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 4000Å which was attributed to Ti II ($\lambda\lambda$ 4395Å, 4444Å and 4468Å) absorption (Filippenko et al. 1992b, Mazzali et al. 1997). Other supernovae showing remarkable deviations are SN 1990a, 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 ~30 days after blue maximum (Li et al. 2004, 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 pre-maximum 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 $\Delta m_{15}$ (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 (Piermattei 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
Supernova Search. The position of the supernova was reported by Biggs (2004) to be R.A. = $06^h45^m43.5^s$ ± 0′.1, Dec. = $-31^\circ13^\prime52.5^\prime$ ± 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 8 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 × 1024 pixel$^2$ CCD camera attached to the f/13 Cassegrain 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 × 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 BVR$\_c$, 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 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 Adopted BVRI 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$_{\text{obs}}$, V$_{\text{obs}}$, R$_{\text{obs}}$, and I$_{\text{obs}}$) and standard (B$_{\text{st}}$, V$_{\text{st}}$, R$_{\text{st}}$, and I$_{\text{st}}$) BVR$\_c$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 BVR$\_c$I$\_c$ magnitudes of SN 2004S based on our observations are provided in Table 2 along with errors.

3 UBVRIC 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

| 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 |

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$^1$ IRAF is distributed by the National Optical Astronomy Observatory, USA.
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Table 2. BVRc and Ic 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)     | Rc (mag)   | Ic (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 | 14.64 ± 0.051 | 14.85 ± 0.063 |
| 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 | 17.66 ± 0.051 | 17.48 ± 0.050 | 15.12 ± 0.061 |
| 2004 02 18.601 | 2453054.1011 | 15.48 ± 0.022 | 14.91 ± 0.041 | 15.04 ± 0.051 | 15.11 ± 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 |

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

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. (1996a, 1996b). Hamuy et al. (1996a) 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 χ² minimizing technique which solved simultaneously for the epoch of maximum brightness in blue band tBmax and the magnitudes B(tBmax), V(tBmax) and Ic(tBmax). We refer to these magnitudes as B(tBmax), V(tBmax) and Ic(tBmax) in the paper. One set of BVI templates from Hamuy et al. (1996a), that for SN 1992al, provided a much better fit, as judged by the value of the reduced χ², than all others. We also found that the SN 1992al template (Hamuy et al. 1996a) fit our data better than the parametrized multiband templates given by Riess et al. (1996). The time for Bmax obtained using templates given by Riess et al. (1996) was two days later than that obtained from Hamuy et al. (1996a). The similarity in behavior between SN 2004S and SN 1992al is remarkable. Even in Ic 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 \cite{Suntzeff:2004}. 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) and Krisiunas et al. (2003) and Krisiunas et al. (2004d) 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 magnitude of the two sets. However, our V magnitudes are fainter by 0.03 mag and I 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 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 \cite{Leibundgut:1988}. According to the best fit template, SN 2004S would have reached maximum brightness in I 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\textsubscript{max}), V(t\textsubscript{max}) and I(t\textsubscript{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\textsubscript{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\textsubscript{max}), V(t\textsubscript{max}) and I(t\textsubscript{max}). From these we calculate another set of E(B − V), E(B − I), E(V − I) using intrinsic colours at t\textsubscript{max} \cite{Nobili: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\textsubscript{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.

We next calculate the amount of selective extinction expected from galactic extinction law, all along the line of sight towards SN 2004S. Using R\textsubscript{c} = 3.1 and E(B − V) = 0.18 ± 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 \cite{Schlegel: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\textsubscript{max} as obtained using the templates of SN 1992al are fairly representative of the sample SN Ia of \cite{Hamuy:1996}. Further, we use these magnitudes to calculate the peak luminosity of SN 2004S in § 4.

Hamuy et al. (1996a) do not present R\textsubscript{c} band templates. In order to compare our R\textsubscript{c} band light curve we construct an expected light curve using \(V − R\textsubscript{c}\) intrinsic colours \cite{Nobili:2003} and the V band template of SN 1992al \cite{Hamuy:1996b}. We use for selective extinction, \(E(V − R\textsubscript{c})\) 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\textsubscript{max}), the derived R\textsubscript{c} band light curve represents the observed data well.

also seen in Figure 3, is a pronounced second maximum in I\textsubscript{c} band displayed by SN 2004S. This second maximum is reached nearly 26 days after the B maximum. The magnitude of the second I\textsubscript{c} maximum is given in Table 4. Such behavior has also been noted for some other SNe Ia \cite{Ford:1993, Suntzeff:1993, Lira:1998, Meikle:2001, Elias:1981, Elias:1983, Li:2001}. The second maxima in the I\textsubscript{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 \cite{Elias:1981, Pinto:2000}.

We estimated the characteristic parameter ∆m\textsubscript{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 ∆m\textsubscript{15} of 1.11. We also calculated ∆m\textsubscript{15} by taking the

| 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\textsubscript{max}) obtained from the best fit template, intrinsic colours and galactic extinction law R\textsubscript{c} = 3.1. Column 4 are the values obtained using best fit E(B − V) from colour curves and galactic extinction law R\textsubscript{c} = 3.1. |
|-----------------|-----------------|-----------------|-----------------|
| from fits to | at t(B\textsubscript{max}) | template fits | galactic |
| colour curves | E(B − V) | E(B − I) | E(V − R\textsubscript{c}) | E(V − I) | E(R\textsubscript{c} − I\textsubscript{c}) | extinction law |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.18 ± 0.054 | 0.20 ± 0.095 | 0.18 ± 0.053 |
| 0.34 ± 0.068 | 0.47 ± 0.112 | 0.40 ± 0.122 |
| 0.08 ± 0.068 | 0.10 ± 0.031 |
| 0.17 ± 0.073 | 0.27 ± 0.122 | 0.22 ± 0.069 |
| 0.09 ± 0.076 | 0.12 ± 0.037 |
B band peak magnitude obtained by the template fit and the observed B band magnitude after ~ 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 ~ 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 \( H_0 = 65 \text{ km sec}^{-1} \text{ Mpc}^{-1} \) and the radial velocity of MCG-05-16-021 corrected for Local Group infall onto Virgo as \( v_r = 2516 \text{ km sec}^{-1} \) 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(\( t_B_{\text{max}} \)) in different bands are \( M^B_{B_{\text{max}}} = -19.05 \pm 0.23 \), \( M^V_{V_{\text{max}}} = -18.96 \pm 0.18 \), \( M^R_{R_{\text{max}}} = -18.82 \pm 0.15 \) and \( M^I_{I_{\text{max}}} = -18.58 \pm 0.14 \). Altavilla et al. (2004) suggests another method for estimating absolute magnitude using a relation between \( M_{\text{max}} \) and \( \Delta m_{15} \). Adopting the values of linear fit coefficients of \(-19.61 \pm 0.04 \) and \( 1.10 \pm 0.15 \) as given by Altavilla et al. (2004), we obtain \( M^B_{\text{max}} = -19.43 \pm 0.08 \). The \( M^B_{\text{max}} \) 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 1990), the integrated flux in UBVR,Ic bands provides a meaningful estimate of the bolometric luminosity, which is directly related to the amount of radioactive nickel synthesized and ejected in the explosion. Supplementing our data in BVR, Ic bands and with U band observations reported by Krisiunas (2004b), we construct a bolometric light curve using de-reddened magnitudes and the estimated distance modulus till ~ 40 days after \( t_B_{\text{max}} \). The first U band observation was 3.105 days after \( t_B_{\text{max}} \). 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. (1993). The contribution from the U band at \( t_B_{max} \) is ~ 18.24 % and that from the Ic band is ~ 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 \( t_B_{\text{max}} \). 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 \( t_B_{\text{max}} \). We derive a peak bolometric luminosity of \( L = 8.715 \times 10^{42} \text{ erg sec}^{-1} \). The bolometric peak is

![Figure 3. UBVR,Ic 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 Krisiunas (2004b). Uncertainties in the data are smaller than the size of the points.](image)

| 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)** | 06h45m43.s5 \( \pm \) 0.1 |
| **Dec (2000)** | \( -31^\circ 13' 32.3'' \) \( 0.1 \) |
| **Offset from the nucleus** | 47' .2 W & 2' .5 S |
| **Spectrum** | Type Ia |
| **Radial velocity** | 2731 \( \pm \) 36 |
| **from galaxy redshift** | 2730 \( \pm \) 42 (LEDA) |
| **Radial velocity corrected for LG infall onto Virgo** | 2516 (LEDA) |
| **Expansion velocity of the SN** | 9300 \( \text{ km sec}^{-1} \) |
| **Distance modulus** | \( \mu = 32.94 \text{ mag} \) |
| **Time of B maximum (JD)** | 2453039.42 |
| **Magnitudes at \( t_B_{\text{max}} \)** | |
| B(\( t_B_{\text{max}} \)) | 14.45 \( \pm \) 0.05 |
| V(\( t_B_{\text{max}} \)) | 13.36 \( \pm \) 0.07 |
| R(\( t_B_{\text{max}} \)) | 14.39 \( \pm \) 0.07 |
| I(\( t_B_{\text{max}} \)) | 14.52 \( \pm \) 0.09 |
| **Absolute Magnitudes at \( t_B_{\text{max}} \)** | |
| \( M^B_{\text{max}} \) | \( -19.05 \pm 0.23 \) |
| \( M^V_{\text{max}} \) | \( -18.96 \pm 0.15 \) |
| \( M^R_{\text{max}} \) | \( -18.82 \pm 0.18 \) |
| \( M^I_{\text{max}} \) | \( -18.58 \pm 0.14 \) |
| **Adopted Total Extinction** | |
| \( A_B \) | 0.716 \( \pm 0.220 \) |
| \( A_V \) | 0.542 \( \pm 0.167 \) |
| \( A_R \) | 0.439 \( \pm 0.135 \) |
| \( A_I \) | 0.320 \( \pm 0.098 \) |
| **Magnitude of secondary** | 15.020 |
| **\( I_{\text{c max}} \) (from template)** | 1.11 |
| **\( \Delta m_{15} \) in B from template** | 1.26 \( \pm 0.061 \) |
| **Decline rate per day \( \sim \) 8 days after \( t_B_{\text{max}} \)** | |
| B band | 0.115 \( \pm \) 0.029 |
| V band | 0.054 \( \pm \) 0.014 |
| Rc band | 0.055 \( \pm \) 0.035 |
| Ic band | 0.034 \( \pm \) 0.048 |
The peak radiated luminosity is expected to be comparable by errors (dashed lines) on both sides. Filled circles represent colours obtained from our observations, and open circles are from observations reported by others.

Figure 4. Color curves of SN 2004S. The middle (solid) line in each panel shows the extinction corrected colour curve bounded by the radioactivity is still being trapped and thermalized. near the time of maximum light most of the energy released under the understanding that radioactivity powers the light curve and mass using the method outlined by Branch (1992). It is understood that radioactivity powers the light curve and derived M\text{Ni} for SN 2004S with corresponding values for the sample of Contardo et al. (2004) 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\text{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\text{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 Krisiunas et al. (2004d). These measurements indicate that SN 1991T was only slightly overluminous, comparable to Type Ia SNe with similar values of \( \Delta m_{15} \). Contardo 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 \( \Delta m_{15} \): 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.

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

where \( \alpha \) 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 \( t_\text{R} \) (the rise time) and M\text{Ni} is the synthesized mass of \(^{56}\text{Ni}\). The B band rise time \( (t_R) \) is related to the post peak B band decline rate (\( \beta \)) in mag per 100 days as \( t_R = 13 + 0.7 \beta \). In the case of SN 2004S \( \beta = 8.45 \), which gives a rise time of 18.915 days.

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

Contardo et al. (2004) have calculated the bolometric luminosity and the ejected nickel mass for several SN Ia from UBVI bolometric peak fluxes. In Table 5 we compare \( M_{\text{Ni}}^{\text{lim}} \), \( \Delta m_{15} \), the peak bolometric luminosity and derived \( M_{\text{Ni}} \) for SN 2004S with corresponding values for the sample of Contardo et al. (2004) 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\text{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\text{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 Krisiunas et al. (2004d). These measurements indicate that SN 1991T was only slightly overluminous, comparable to Type Ia SNe with similar values of \( \Delta m_{15} \). Contardo 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 \( \Delta m_{15} \): 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.

Figure 5. Bolometric light curve for SN 2004S. The solid line shows the Bolometric light curve constructed from UBVR bands and the dash-dotted line shows the bolometric light curve derived from BVI fits of Hamuy et al. (1996).
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     | \(\Delta m_{15}\) | \(B_{\text{max}}\) | \(V_{\text{max}}\) | \(I_{\text{max}}\) | \(B_{\text{max}}-V_{\text{max}}\) | \(M_{\text{bol}}^{\text{max}}\) | \(M_{\text{bol}}^{\text{max}}\) | \(M_{\text{bol}}^{\text{max}}\) |
|--------|-------------------|-------------------|-------------------|-------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 1992al | 1.11(0.05)        | 14.60(0.07)      | 14.05(0.06)      | 14.94(0.06)      | -0.05(0.03)                 | -19.47(0.32)                | -19.42(0.31)                | -19.13(0.31)                |
| 2004S  | 1.26(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, \(\Delta m_{15}\) and \(^{56}\)Ni masses of few SN Ia

| SN     | \(M_B\) (mag) | \(\Delta m_{15}\) | \(\log L_{\text{bol}}\) (erg sec \(^{-1}\)) | \(M_{\text{Ni}}\) |
|--------|---------------|-------------------|------------------------------------------|-----------------|
| 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            |
| 1999qw | -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 quite similar, although SN 2004S may be marginally less luminous particularly in the I 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,Ic 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 \(\Delta m_{15}\) 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 \(8.715 \times 10^{42}\) 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 \(\Delta m_{15}\) 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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