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Photometric Investigation of Bright Type II-P Supernova 2004dj

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Abstract

CCD *UBVRI* photometry is presented for type II SN 2004dj for about 1200 days, starting on day 2 past discovery. The photometric behaviour is typical of SNe II-P, although some minor peculiarities are noticed. We compare the photometric data for the host cluster S96 before and after the SN 2004dj outburst and do not find any significant changes.

1 INTRODUCTION

The brightest supernova of the past decade, SN 2004dj, was discovered by K. Itagaki (Nakano et al., 2004) on 2004 July 31.76 UT in the nearby SBcd galaxy NGC 2403. The spectra taken immediately after discovery indicated it to be a type II-P event found long after the outburst (Patat et al., 2004). The object was also detected in radio (Stockdale et al., 2004), infrared (Sugerman and Van Dyk, 2005; Kotak et al., 2005) and X-ray bands (Pooley and Lewin, 2004). The optical photometry for SN 2004dj was published by Korcáková et al. (2005), Zhang et al. (2006), Vinkó et al. (2006). Spectroscopic observations were reported by Vinkó et al. (2006) and Korcáková et al. (2005). The results show that SN 2004dj is a typical SN II-P, regarding both photometric and spectral evolution. The ejected mass is estimated to be about 10 $M_{\odot}$, and the mass of synthesized ^{56}Ni was about 0.02 $M_{\odot}$. BVR light curves and spectra in the nebular phase were presented by Chugai et al. (2005) who pointed out strong asymmetry of the Hα emission line at the nebular epoch. The photometric observations by Chugai et al. (2005) were reprocessed by us, and the magnitudes presented here supersede the data reported in Chugai et al. (2005). Spectropolarimetry reported by Leonard et al. (2006) indicates strong departure from spherical symmetry for the inner ejecta. Asymmetry of ^{56}Ni ejecta that results in the observed asymmetry of the Hα emission line and the possibility that this effect can also account for the polarization of SN radiation was discussed by Chugai (2006).

The association of SN 2004dj with the compact cluster Sandage 96 attracted particular attention, the data on this cluster were reported by Yamaoka et al. (2004), Maíz-Apellániz et al. (2004), Wang et al. (2005), Chugai et al. (2005), and Vinkó et al. (2006). The data suggests a cluster age of 14 – 20 Myr, which results in probable SN progenitor mass of 12 – 15 $M_{\odot}$.

2 OBSERVATIONS AND REDUCTIONS

We started observations of SN 2004dj on 2004 August 2, two days after the discovery, but the field was also imaged at the 1-m reflector of the Special Astrophysical Observatory on 2001 January 19, long before the explosion.

The observations of supernova were carried out with the following telescopes and CCD cameras: the 1-m reflector of the Special Astrophysical Observatory equipped with an

EEV42-40 CCD (S100) (only the images obtained before the discovery of the supernova were taken with an Electronika K-585 CCD); the 70-cm reflector of the Sternberg Institute in Moscow (M70) with Apogee AP-7p (a) or AP-47p (b) cameras; the 60-cm reflector of the Sternberg Institute's Crimean Laboratory (C60) with Princeton Instruments VersArrayB1300 (c), AP-47p , AP-7p, or SBIG ST-7 (d) CCD cameras; the 50-cm Maksutov telescope of the Sternberg Institute's Crimean Laboratory with a Meade Pictor 416XT CCD camera (C50).

During three years of observations, different filter sets were used at M70 and C60, they are identified by numbers after the code for the telescope and CCD camera. The color terms were derived solving equations from Tsvetkov et al. (2006), they are reported in Table 1. The observations at C50 were carried out only with a V filter close to the standard system, and no correction was applied.

Table 1. Color terms for different telescope/camera/filter combinations

Code	K_u	K_b	K_v	K_r	K_i
M70a1		–0.11	–0.032	–0.24	–0.38
M70a2		–0.14	–0.023	–0.12	–0.38
M70b	–0.05	–0.21	–0.023	0.09	–0.39
C60a		–0.10	–0.002	–0.45	–0.37
C60b1	–0.03	–0.21	–0.017	0.09	–0.38
C60b2	–0.05	–0.16	–0.033	–0.03	–0.45
C60c	–0.06	–0.10	–0.026	–0.025	–0.43
C60d		–0.34	–0.02	0.05	
S100		–0.10	0.09	0.036	

The standard image reductions and photometry were made using IRAF[1].

Photometric measurements of the SN were made relative to local standard stars using PSF-fitting with IRAF DAOPHOT package. We did not try to subtract prediscovery images from the images with supernova.

The magnitudes of local standard stars were calibrated on photometric nights, when photometric standards were observed at different airmasses. They are presented in Table 2. The image of the SN with marked local standards is shown in Fig 1.

Table 2. Magnitudes of local standard stars

Star	U	σ_U	B	σ_B	V	σ_V	R	σ_R	I	σ_I
1	10.43	0.02	10.48	0.02	9.95	0.02	9.62	0.02	9.35	0.02
2	14.82	0.07	14.72	0.03	14.08	0.02	13.68	0.02	13.35	0.02
3	17.21	0.13	16.48	0.03	15.56	0.02	15.05	0.02	14.61	0.02
4	14.78	0.02	14.31	0.02	13.50	0.01	12.97	0.04	12.63	0.02
5	15.78	0.04	15.45	0.02	14.75	0.02	14.28	0.04	13.98	0.02

The magnitudes for our stars 1, 2, 3, 5 were derived by Vinkó et al. (2006), and for stars 2, 3, 4, 5, by Stetson[2]. The differences between our magnitudes and those from Vinkó et al. (2006) are quite significant, especially in the B band, the mean differences are: $\overline{\Delta B} = -0.14 \pm 0.03; \overline{\Delta V} = -0.09 \pm 0.02; \overline{\Delta R} = -0.05 \pm 0.02; \overline{\Delta I} = -0.06 \pm 0.01$. The magnitudes from Stetson are in a much better agreement with our data, the mean differences are: $\overline{\Delta B} = -0.02 \pm 0.01; \overline{\Delta V} = 0.00 \pm 0.01; \overline{\Delta R} = 0.01 \pm 0.02$.

The good agreement of our data with the magnitudes from Stetson suggests that our calibration is more reliable than that by Vinkó et al. (2006).

The photometry for SN 2004dj is reported in Table 3.

[1]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by AURA under cooperative agreement with the National Science Foundation

[2]http://www2.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/ community/STETSON/standards/

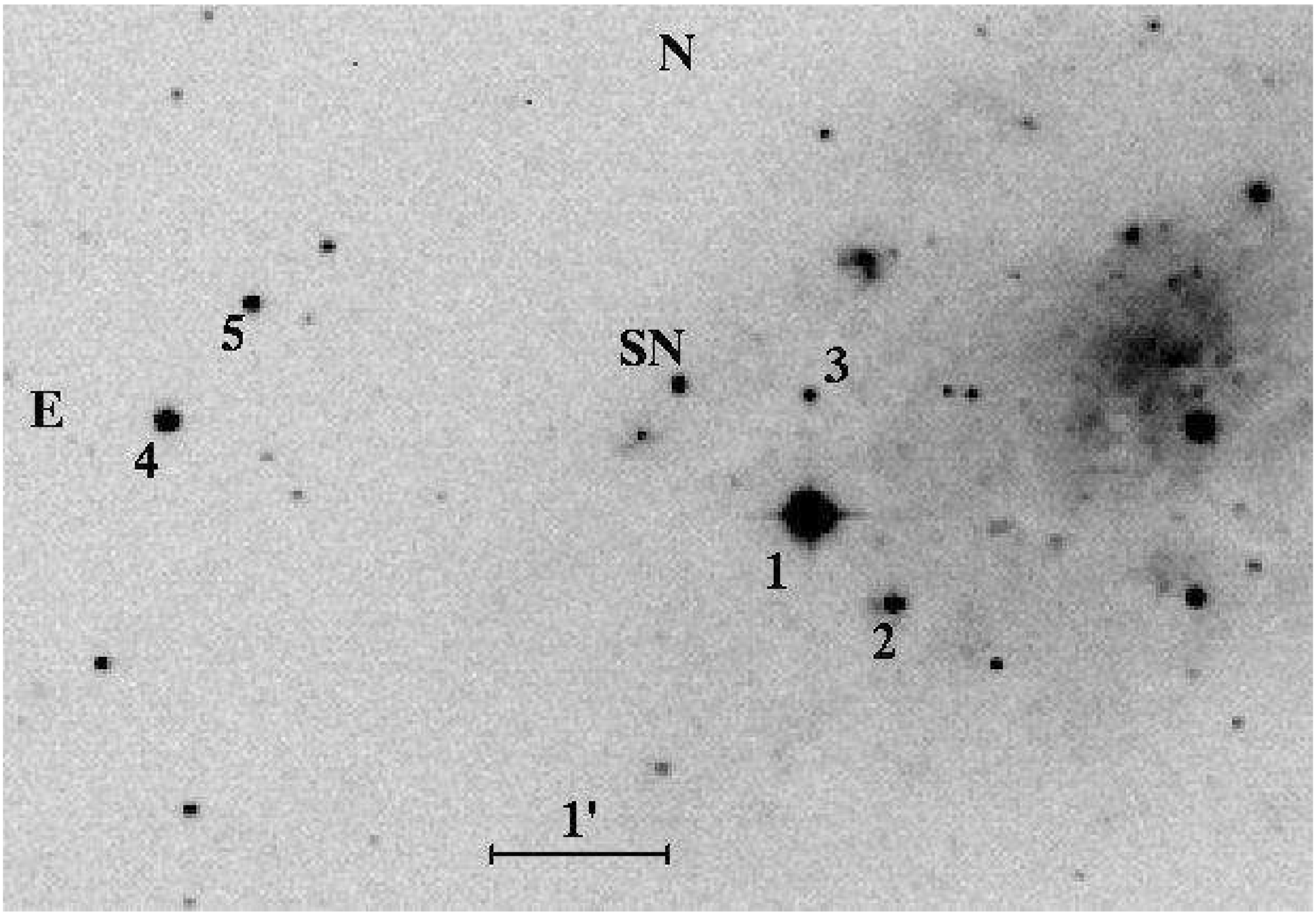

Figure 1. SN 2004dj with local standard stars

3 THE LIGHT AND COLOR CURVES

The light curves are presented in Fig. 2. They are typical of SNe II-P, but only a small part of the plateau was covered by observations. After the fast decline from the plateau, prominent flattening, or a secondary plateau, is evident on the light curves in the R and I bands, which lasts about 160 days, and only after about JD 2453480 the linear decline begins. At about JD 2453800, the light curves in all bands flatten, as the cluster S96 becomes the dominant source of luminosity. We can subtract the luminosity of the cluster from magnitudes obtained for the sum of the cluster and supernova. For subtraction, we used the B, V, R magnitudes of S96 derived from images obtained before the explosion, and we adopted $I_{S96} = 17.32$ from our last image in this band. The resulting light curves are shown in Fig. 3. The linear fits to the magnitudes in the JD 2453500–2453800 time interval give the following decline rates (in mag day^{-1}): 0.0063 in B, 0.0096 in V, 0.010 in R, and 0.011 in the I band. In all bands except B, the rate is very close to the decay slope of ^{56}Co, which is 0.0098 mag day^{-1}.

Table 3. Observations of SN 2004dj

JD 2450000+	U	σ_U	B	σ_B	V	σ_V	R	σ_R	I	σ_I	Telescope
1929.48			18.61	0.04	18.22	0.03	17.82	0.03			S100
3220.31			12.49	0.02	11.89	0.02	11.51	0.02	11.36	0.02	M70a1
3222.32			12.49	0.02	11.89	0.02	11.51	0.02	11.33	0.02	M70a1
3238.27			12.92	0.03	11.96	0.02	11.54	0.02	11.34	0.02	M70a1
3242.52			12.90	0.02	11.97	0.02	11.58	0.02	11.31	0.02	M70a1
3244.57	13.80	0.03	12.91	0.02	11.97	0.02	11.53	0.02			C60c
3248.55	13.92	0.06	12.95	0.02	12.01	0.02	11.61	0.02			C60c
3249.47			12.97	0.02	12.05	0.02	11.59	0.02	11.44	0.02	M70a1
3250.48					12.03	0.02					C50
3251.51					12.06	0.02					C50
3253.47					12.05	0.02					C50
3254.52			13.02	0.02	12.07	0.02	11.65	0.02	11.36	0.02	M70a1
3255.50					12.07	0.02					C50
3255.56	14.11	0.05	13.09	0.03	12.07	0.02	11.69	0.02	11.40	0.02	C60c
3256.24					12.10	0.02					C50
3257.22					12.09	0.03					C50
3257.58	14.20	0.04	13.11	0.03	12.11	0.02	11.65	0.02	11.41	0.03	C60c
3259.60					12.12	0.02	11.71	0.03	11.46	0.03	C60c
3261.60	14.20	0.11	13.12	0.03	12.15	0.02	11.70	0.03	11.41	0.03	C60c
3263.54			13.20	0.02	12.22	0.02	11.79	0.02	11.56	0.02	M70a1
3269.51			13.32	0.03	12.32	0.02	11.89	0.02	11.60	0.02	M70a1
3294.49	16.16	0.09	14.75	0.03	13.79	0.03	13.36	0.02	13.01	0.03	M70b
3307.49			15.98	0.03	14.63	0.02	14.21	0.02	13.78	0.03	M70b
3309.63			15.95	0.03	14.67	0.02	14.16	0.05	13.74	0.02	C60c
3312.60			15.94	0.03	14.72	0.02	14.23	0.02	13.72	0.03	M70a1
3315.57	17.16	0.10	15.96	0.03	14.74	0.02	14.22	0.02	13.80	0.03	C60c
3317.51			15.98	0.03	14.81	0.02	14.29	0.02	13.86	0.03	C60a
3318.54	17.11	0.15	15.98	0.03	14.77	0.02	14.34	0.02	13.82	0.03	C60c
3320.52	17.31	0.09	16.02	0.03	14.80	0.02	14.31	0.02	13.83	0.02	C60c
3321.56	17.32	0.13	16.03	0.03	14.81	0.03	14.33	0.04	13.85	0.03	C60c
3321.62			16.07	0.02	14.84	0.02	14.27	0.02			S100
3323.53	17.30	0.09	16.03	0.04	14.85	0.03	14.38	0.03	13.85	0.03	C60c
3331.53	17.35	0.10	16.09	0.03	14.93	0.02	14.39	0.02	13.86	0.02	C60c
3355.54			16.27	0.03	15.21	0.03	14.45	0.02			C60c
3357.54			16.29	0.02	15.21	0.02	14.44	0.03			C60c
3358.54			16.26	0.02	15.19	0.03	14.45	0.02			C60c
3361.57			16.30	0.04	15.23	0.03	14.52	0.03			C60c
3385.36			16.53	0.02	15.46	0.02	14.53	0.02			S100
3386.38			16.48	0.02	15.44	0.02	14.51	0.02			S100
3387.42			16.52	0.02	15.45	0.02	14.51	0.02			S100
3389.40			16.41	0.04	15.49	0.03	14.52	0.02	14.09	0.02	M70b
3406.33			16.46	0.03	15.56	0.03	14.59	0.02	14.15	0.02	M70b
3412.28			16.45	0.05	15.67	0.04	14.61	0.03	14.16	0.03	M70b
3427.38			16.58	0.06	15.68	0.05	14.67	0.04	14.21	0.03	M70b
3432.38			16.50	0.08	15.70	0.05	14.72	0.04	14.31	0.04	M70b
3436.49			16.63	0.02	15.75	0.02	14.83	0.02			S100
3437.27			16.62	0.02	15.77	0.02	14.86	0.02			S100
3444.28			16.72	0.06	15.83	0.05	14.80	0.04	14.41	0.03	M70b
3446.40			16.71	0.04	15.87	0.04	14.82	0.03	14.43	0.03	M70b
3456.40			16.67	0.04	15.95	0.04	14.87	0.03	14.46	0.03	M70b
3465.33			16.71	0.05	16.02	0.06	14.98	0.05	14.62	0.06	M70b
3500.40					16.21	0.03					S100
3509.32			16.92	0.05	16.22	0.06	15.35	0.04	14.97	0.05	M70a2
3530.27			17.03	0.03	16.33	0.03	15.51	0.03			S100

Table 3. Continued

JD 2450000+	U	σ_U	B	σ_B	V	σ_V	R	σ_R	I	σ_I	Telescope
3580.46					16.75	0.07	15.92	0.04	15.71	0.05	M70a2
3581.53					16.75	0.03					C50
3587.47			17.31	0.05	16.75	0.04	15.96	0.04	15.75	0.04	M70a2
3588.54			17.34	0.03	16.84	0.02	16.03	0.02			C60b1
3593.46			17.34	0.04	16.77	0.07	15.97	0.03	15.87	0.05	M70a2
3593.54			17.34	0.03	16.96	0.03	16.10	0.02			C60b1
3597.54			17.52	0.04	16.98	0.02	16.12	0.03			C60b1
3607.52			17.27	0.05	16.98	0.06	16.06	0.04	15.89	0.07	M70a2
3612.55			17.49	0.04	16.99	0.04	16.26	0.04	16.06	0.07	C60b1
3621.44			17.39	0.09	17.02	0.08	16.20	0.06	16.03	0.06	M70a2
3621.58							16.35	0.06			C60c
3628.50			17.35	0.04	17.08	0.04	16.26	0.03	16.06	0.04	M70a2
3647.48			17.55	0.05	17.15	0.06	16.29	0.05	16.13	0.08	M70a2
3676.55			17.67	0.04	17.40	0.03	16.70	0.03	16.47	0.05	C60b1
3684.44			17.80	0.04	17.46	0.04	16.76	0.03	16.54	0.04	C60b1
3728.44			17.88	0.03	17.63	0.03	17.05	0.02			C60c
3737.37					17.65	0.40	17.16	0.07			C60d
3738.43			18.00	0.06	17.66	0.05	17.10	0.03			C60d
3744.42							17.09	0.08			C60d
3801.47			17.95	0.10	18.09	0.15	17.30	0.09	16.95	0.10	M70a2
3822.27			18.12	0.08	17.84	0.10	17.24	0.06	17.00	0.08	M70a2
3826.30			17.90	0.03	17.72	0.03	17.27	0.03			S100
3827.26			18.13	0.04	17.84	0.03	17.40	0.03			S100
3859.33			18.29	0.16	17.94	0.15	17.36	0.10	16.96	0.07	M70a2
3886.27			18.07	0.03	17.82	0.02	17.42	0.02			S100
3887.27			18.12	0.04	17.93	0.03	17.45	0.03			S100
3972.54					17.96	0.03					C50
4034.76			18.22	0.04	17.97	0.03	17.60	0.03			S100
4035.76			18.32	0.04	18.07	0.03	17.74	0.03			S100
4086.54			18.03	0.07	17.97	0.04	17.53	0.04			C60c
4091.57			18.15	0.04	17.87	0.04	17.52	0.05			C60c
4146.47			18.36	0.03	18.09	0.03	17.72	0.02			S100
4181.44			18.40	0.03	18.09	0.03	17.76	0.03			S100
4418.52			18.31	0.04	18.12	0.03	17.77	0.03	17.32	0.11	C60b2
4426.46					18.00	0.04					C50
4428.54					18.03	0.05					C50

Fig. 4 presents the comparison of our results with the data by Vinkó et al. (2006) and Zhang et al. (2006), and also the match between the light curves of SN 2004dj and typical SNe II-P 1999em (Leonard et al., 2002; Elmhamdi et al., 2003; Hamuy et al., 2001) and 2003gd (Hendry et al., 2005). The agreement of our data with the results by Vinkó et al. (2006) is quite satisfactory, taking into acount the difference between the calibrations of local standards and non-standard transmission of some of our filters. The VRI magnitudes by Zhang et al. (2006) were transformed to the standard system from photometry in their intermediate-band filters, thus large systematic differences can be expected, and we really see strong departures from our light curve in the I band and in the R band at late stages. A comparison of the light curves of type II-P SNe 2004dj, 1999em and 2003gd reveals diversity of photometric evolution for objects of this class. We align the light curves in magnitudes so that they coincide at the plateau, and shift them in time to match the early decline from the plateau. The differences are evident: SN 2003gd has the largest drop from the plateau to the start of the exponential tail and

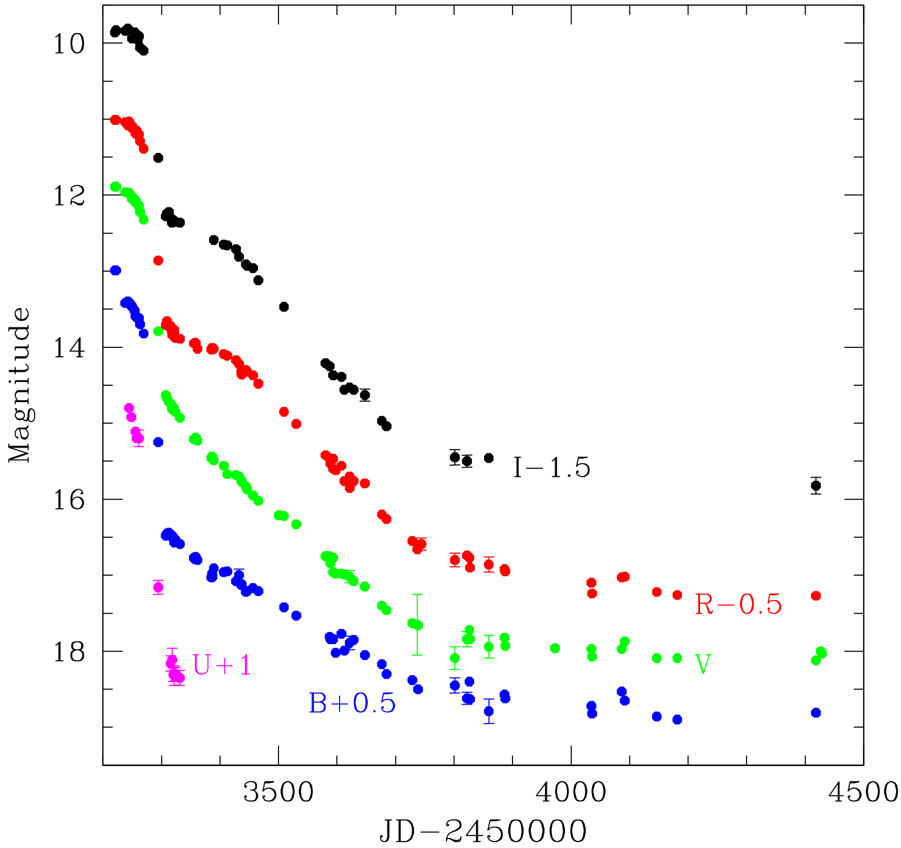

Figure 2. *UBVRI* light curves for SN 2004dj. The error bars are shown only if they exceed the size of a point on this and the following figures

so sign of flattening; for SN 1999em, the decline in about one magnitude less and a small flattening is evident. The light curves of SN 2004dj lie between the curves for these two SNe, and the flattening in the R and I bands is the most pronounced.

The color curves for the same objects are shown in Fig. 5. The color curves of SNe 1999em and 2003gd were shifted for better alignment with the curves for SN 2004dj in the first week after discovery. The resulting shifts for SN 1999em in $U-B$, $B-V$, $V-R$, and $R-I$ colors are respectively –0.9, –0.4, –0.1, and –0.1. For SN 2003gd in the same colors, except $U-B$, they are: –0.2, 0, –0.1. The data clearly shows that SN 2004dj is bluer than SNe 1999em and 2003gd, and the shape of its $V-R$ color curve is different after JD 2453280. As the total interstellar extinction for SNe 1999em and 2003gd is quite small, with estimates of $E(B-V)$ in the range between 0.075 and 0.1 for SN 1999em and between 0.13 and 0.14 for SN 2003gd (Elmhamdi et al., 2003; Hendry et al., 2005), our result suggests that extinction for SN 2004dj is also small, and perhaps the colors are intrinsically bluer. We adopt for SN 2004dj $E(B-V) = 0.07$, the value preferred by Vinkó et al. (2006).

The absolute V-band light curves of SNe II-P 2004dj, 1999em, 2003gd and 2005cs (Tsvetkov et al., 2006) are compared in Fig. 6. We adopted the following values of distance and extinction. SN 2004dj: $D = 3.1$ Mpc, $A_V = 0.22$; SN 1999em: $D = 11.7$ Mpc, $A_V = 0.3$; SN 2003gd: $D = 9.3$ Mpc, $A_V = 0.43$; SN 2005cs: $D = 8.3$ Mpc,

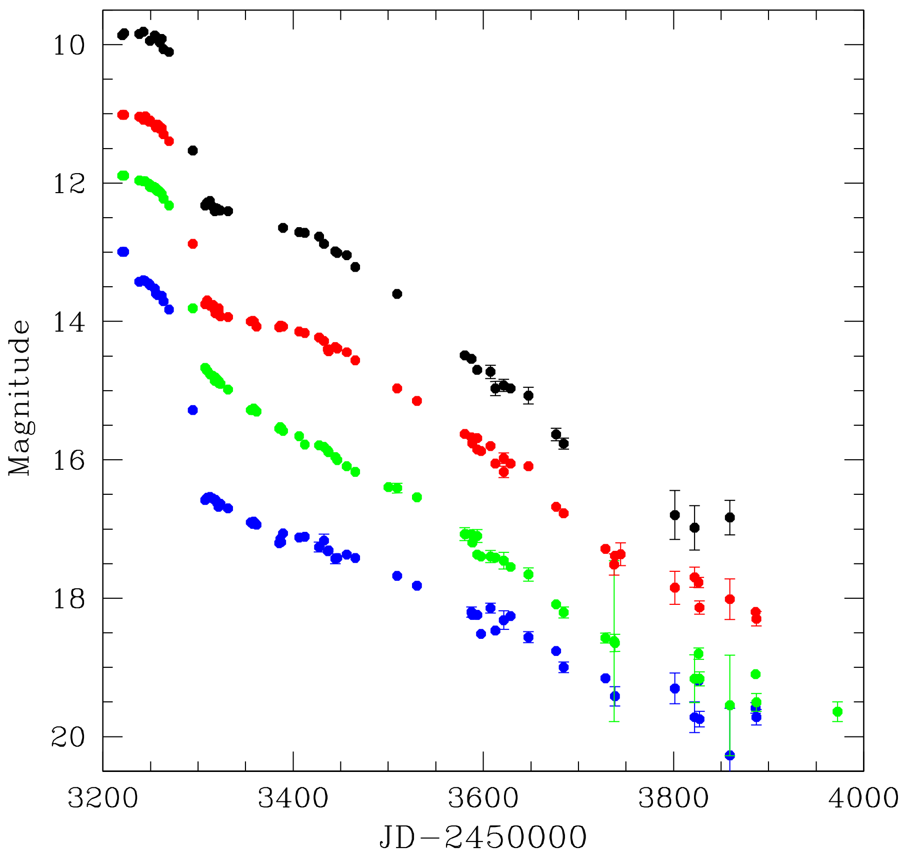

Figure 3. *BVRI* light curves for SN 2004dj after subtraction of the luminosity of the cluster S96. The color coding and shifts of magnitudes are the same as on Fig. 2

$A_V = 0.3$. SN 2004dj is fainter at the plateau than the normal SNe II-P 1999em and 2003gd, but brighter than the subluminous SN 2005cs. At the start of the tail, the luminosity of SN 2004dj is the same as for SN 2003gd.

4 THE CLUSTER S96 BEFORE AND AFTER THE OUTBURST OF SN 2004dj

The observations of the SN 2004dj host cluster S96 attracted much attention, they can reveal the nature of the SN precursor. The data published up to now were obtained before the SN explosion, but we also carried out photometry long after the outburst. The data in Table 3 report our PSF photometry for S96 before the explosion as well as at a very late stage, about 3.4 years past the SN explosion. The results show that the luminosity of the cluster in the R band is the same before and after the explosion, but in the B and V bands, it is slightly brighter after the outburst. If the brightness decline of SN 2004dj continues at the rate we estimate, then at JD 2454420 it is about 25 mag and can add only about 0.002 mag to the luminosity of the cluster. Of course, the use of PSF photometry for a non-stellar object may be unjustified. We geometrically transformed the frames obtained at S100 on JD 2451929 (with the K-585 CCD) and at C60 on JD 2454418 to a common pixel grid defined by the images from S100 on JD 2454181 and performed aperture photometry with identical parameters. The results are in Table 4.

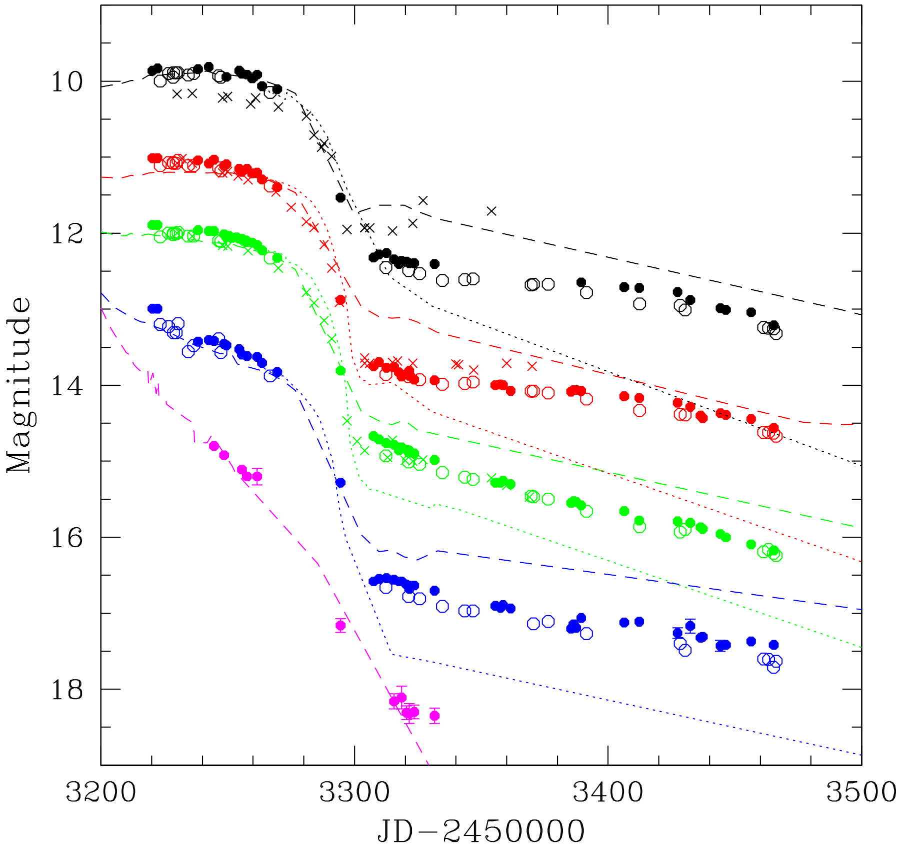

Figure 4. *UBVRI* light curves of SN 2004dj for the first 260 days after its discovery. The color coding and shifts of magnitudes are the same as on Fig. 2. Dots show our data, corrected for the luminosity of cluster S96; circles are for magnitudes from Vinkó et al. (2006); and crosses show the results from Zhang et al. (2006). The dashed curves are the light curves of SN 1999em, and the dotted curves represent the light curves of SN 2003gd

Table 4. Aperture photometry of the cluster S96 before and after the SN explosion

JD 2450000+	B	σ_B	V	σ_V	R	σ_R	Telescope
1929.48	18.41	0.07	17.95	0.05	17.66	0.04	S100(K-585)
4181.44	18.05	0.04	17.86	0.04	17.64	0.05	S100
4418.52	18.29	0.04	17.87	0.03	17.76	0.04	C60b2

We can compare our results to the magnitudes of the cluster S96 before the explosion as estimated by Maíz-Apellániz et al. (2004), Wang et al. (2005), and Vinkó et al. (2006). Their data are, respectively: B = 18.19; 18.29; 18.25; V = 17.93; 18.07; 17.85; R = 17.88; 17.52 (no R-band photometry is given by Maíz-Apellániz et al. 2004). The scatter is quite large, as can be expected for photometry of a non-stellar object superimposed on the bright background of the host galaxy, and our data are in a general agreement with these results.

We may conclude that the brightness of the cluster is the same within the errors of our magnitudes before and after the outburst. The only discordant estimate of B on JD 2454181.44 is likely due to some accidental error, as PSF-photometry on this image gives fainter magnitude than for the frame obtained on JD 2454418.52 at C60. We do not observe the decline of cluster luminosity which is expected after the explosion of a

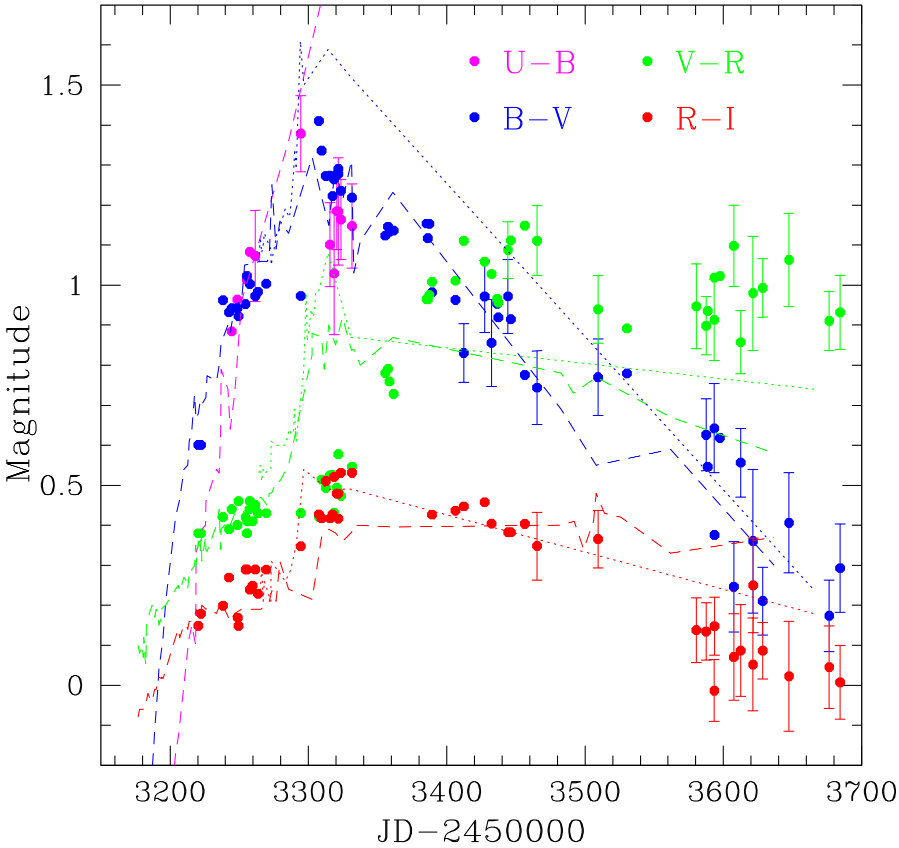

Figure 5. The color curves for SN 2004dj compared to the curves for SN 1999em (dashed) and SN 2003gd (dotted), shifted as reported in the text

supergiant star, but the accuracy of our magnitudes is not sufficient to detect the expected dimming by 0.02–0.1 mag (Maíz-Apellániz et al., 2004; Wang et al., 2005).

5 CONCLUSIONS

We conclude that SN 2004dj is a normal SN II-P, but some peculiarities of its photometric evolution are evident: the flattening of the light curves in the R and I bands after a drop from the plateau is more pronounced than for most of SNe II-P; the shape of the $V-R$ color curve is different from that for typical SNe II-P, and all colors may be systematically bluer. The luminosity at the plateau, $M_V \sim -16$ mag, is quite normal. As the luminosity at the tail is nearly the same for SN 2004dj and SN 2003gd, we may assume that they produce similar amounts of ^{56}Ni. For SN 2003gd, Hendry et al. (2005) obtained $M_{\rm Ni} = 0.016 \pm 0.01\ M_{\odot}$, and this is in a good agreement with the estimates for SN 2004dj from Chugai et al. (2005), Vinkó et al. (2006), and Zhang et al. (2006).

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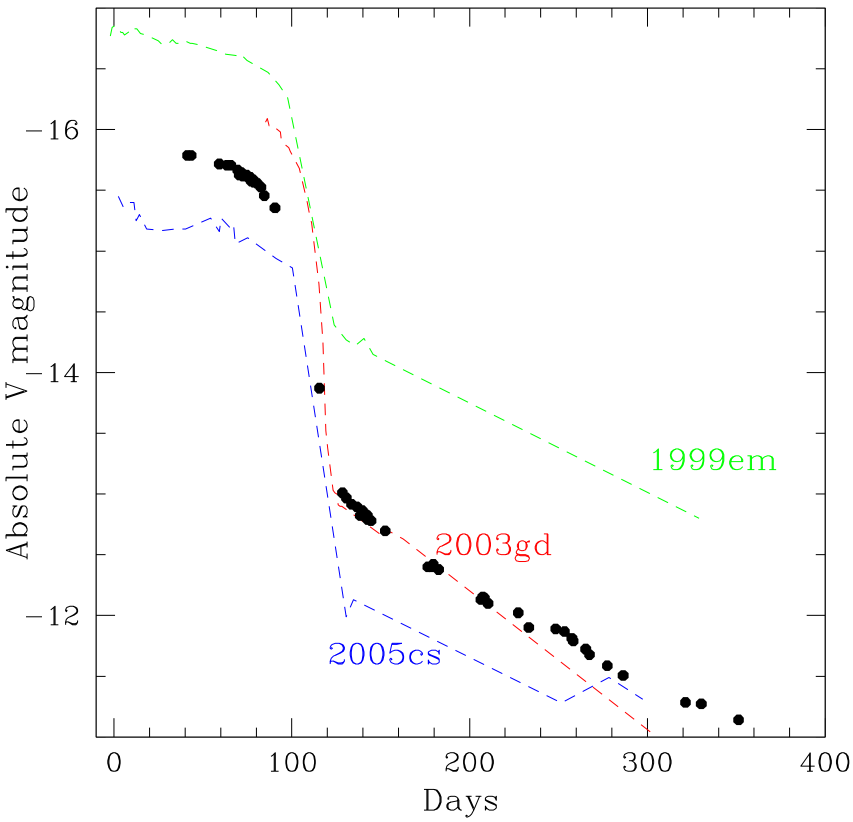

Figure 6. The absolute V-band light curve of SN 2004dj (black dots) compared to the light curves of SNe 1999em, 2003gd, and 2005cs

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