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UBVRI CCD PHOTOMETRY OF THE TYPE Ic SUPERNOVA SN 1994I IN M51: THE FIRST TWO MONTHS

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ABSTRACT

We present *UBVRI* CCD photometry of the Type Ic supernova SN 1994I in M51 which was discovered on April 2, 1994 (UT). *UBVRI* CCD photometry of SN 1994 I were obtained for the period of the first two months from April 4, 1994, using the Seoul National University Observatory 60 cm telescope. The light curves of SN 1994I show several interesting features: (a) SN 1994I reaches the maximum brightness at B-band on April 8.23 (B = 13.68 mag), at V-band on April 9.10 (V = 12.89 mag), and at I-band on April 10.32 (I = 12.48 mag); (b) The light curves around the maximum brightness are much narrower than those of other types of supernovae; (c) The light curves after the peak decline more steeply than those of other types of supernovae; and (d) The colors get redder from $(V-R) \approx 0.2$ mag ($(V-I) \approx 0.3$ mag, $(B-V) \approx 0.7$ mag) on April 4 to $(V-R) \approx 0.6$ mag ($(V-I) \approx 0.9$ mag, $(B-V) \approx 1.3$ mag) on April 18. Afterwards $(V-R)$ colors get bluer slightly (by ~0.005 mag/day), while $(V-I)$ colors stay almost constant around $(V-I) \approx 1.0$ mag. The color at the maximum brightness is $(B-V) = 0.9$ mag, which is ~1 mag redder than the mean color of typical Type Ia supernovae at the maximum brightness. The light curves of SN 1994I are similar to those of the Type Ic supernova SN 1962L in NGC 1073. Adopting the distance modulus of $(m-M)_0 = 29.2$ mag and the reddening of $E(B-V) = 0.45$ mag [Iwamoto et al. 1994, preprint for ApJ], we derive absolute magnitudes at the maximum brightness of SN 1994I, $M_V(\max) = -17.7$ mag and $M_B(\max) = -17.4$ mag. This result shows that SN 1994I was ~2 mag fainter at the maximum brightness compared with typical Type Ia supernovae. A narrower peak and faster decline after the maximum in the light curve of SN 1994I compared with other types of supernovae indicate that the progenitor of SN 1994I might be a lower mass star compared with those of other types of supernovae.

Key Words : Galaxies: individual (M51), Stars: supernovae, Supernovae: individual (SN 1994I) , Photometry

I. INTRODUCTION

Supernova 1994I was discovered in the nearby spiral galaxy M51, on April 2.17, 1994 (UT) (Puckett & Armstrong 1994). SN 1994I is located in a spiral arm, 14″ south and 12″ east of the nuclues of M51 (Figure 1). The right ascension and declination of SN 1994I were measured to be RA(2000) = $13^h\ 29^m\ 54^s.072$ and Dec(2000) = +47° 11′ 30″.50 (Morrison & Argyle 1994). It was as bright as $V \approx 13.5$ mag, when it was discovered. Filippenko *et al.* (1994) checked the R CCD image of M51 which was obtained on March 28, 1994, and found that there was no supernova detectable to a limiting magnitude of $R = 16.2$ mag. According to pre-discovery observations, SN 1994I was 14 mag on March 31.58 (Sasaki & Hazaki 1994). Therefore it is believed that SN 1994I exploded between March 28 and 31. On April 3, SN 1994I was detected in the VLA 1.3cm and 3.6cm observations, giving observed fluxes

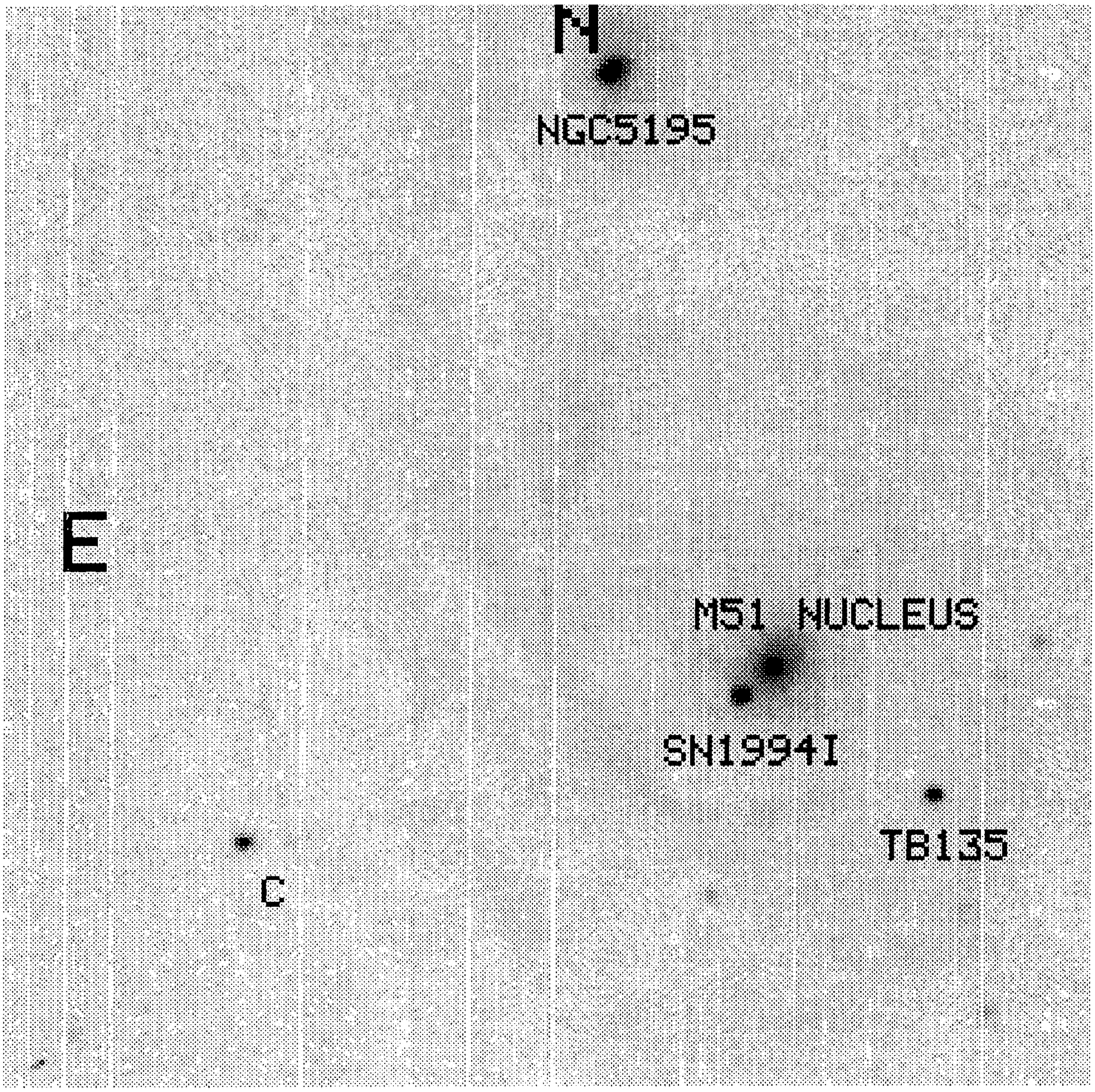

Fig. 1. A V-band CCD image of M51 showing SN 1994I. This image was obtained on April 9, 1994, when SN 1994I reached the maximum brightness. North is at the top and east is to the left. The size of the field is $8'.1 \times 8'.1$. The reference star TB 135 and the check star C are labeled.

of F(1.3cm) = 2.32 ± 0.52 mJy and F(3.6cm) = 0.55 ± 0.01 mJy (Rupen *et al.* 1994). This is one of the earliest detection of supernovae in the radio following the optical discovery of supernovae.

Spectral classification of SN 1994I evolved since it was discovered. Right after the discovery of SN 1994I, Schmidt & Kirshner (1994) classified it as Type II from the optical spectra obtained on April 3. However, Filippenko *et al.* (1994) classified it as Type Ib rather than as Type II from the spectra obtained on April 4, noting that the possible presence of weak H_α features may indicate a Type IIb. Schmidt *et al.* (1994) claimed that SN 1994I is not a Type II on April 5. On April 8, when the supernova reached almost the maximum brightness, Clocchiatti *et al.* (1994) found little He features from the optical spectra of SN 1994I, and classified it as Type Ic. This classification was confirmed

Table 1. *UBVRI* Photometry of TB 135 and Star C

Star	U	B	V	R	I	Reference
TB 135	14.14	14.05	13.44	13.08	12.81	Corwin (1993)
Star C	14.69 ± 0.03	14.35 ± 0.03	13.63 ± 0.03	13.22 ± 0.03	12.93 ± 0.03	This study

by Kirshner (1994) who used the spectra covering a wavelength range of 1600–4700 Åobtained with the Hubble Space Telescope on April 18 and 19. Since then SN 1994I has been classified as Type Ic. Detailed descriptions of the spectra of SN 1994I were recently given by Sasaki *et al.* (1994) and Wheeler *et al.* (1994).

The class of Type Ic supernovae was introduced in the late 1980's (Wheeler & Harkness 1986a) to distinguish between helium-rich and helium-poor Type Ib supernovae. Fundamental criteria for spectral classification of Type Ic supernovae are no H, He and Si features. Type Ic supernovae are very rare compared with other types of supernovae. To date there are only eleven known supernovae which were classified as obvious Type Ic supernovae (see Section 4 for details). Much less is known about the properties of Type Ic supernovae compared with other types of supernovae. SN 1994I is the nearest among the known Type Ic supernovae. Therefore SN 1994I is an ideal target to investigate the characteristics of Type Ic supernovae.

In this paper we present a study of SN 1994I based on *UBVRI* CCD photometry obtained for the first two months since April 4, 1994. During the preparation of this study, *VRI* CCD photometry of SN 1994I for the period April 5 – May 30 was presented by Yokoo *et al.* (1994).

II. OBSERVATIONS AND DATA REDUCTION

(a) Observations

UBVRI CCD images of M51 including SN 1994I were obtained using the Seoul National University Observatory (SNUO) 60cm telescope and the Photometrics PM 512 CCD camera. SNUO is located on the campus of the Seoul National University at the southern area of Seoul in Korea. We started our observations of SN 1994I on April 4, 1994 (UT) and stopped on June 3, when SN 1994I was too faint to be observed with our telescope. The filters used are Johnson-Kron-Cousins *UBVRI* filter set No. 1 of SNUO. The CCD chip has an area of 512 × 512 pixels and the size of the field of view in the CCD image is $8'.1 \times 8'.1$ at the f/7 Cassegrain focus of our telescope. The gain of the CCD is 4.11 electrons/ADU, and the readout noise is 6.2 electrons. We used through our observations 2 × 2 pixels binning mode, for which the pixel scale is $1''.89$/binned pixel. Exposure times ranged from 60 seconds to 240 seconds. Seeing ranged from $5''$ to $10''$, with a mean value of $6''.8$ during our observations. Evening twilight sky flat images were obtained for flattening of the object CCD images. Since the CCD used has poor sensitivity at the short wavelength, only a small number of U images were obtained in the beginning of the observing period. A greyscale map of V CCD image of M51 showing SN 1994I is displayed in Figure 1. This CCD image was obtained on April 9, when SN 1994I reached the maximum brightness, with the exposure time of 180 sec. Figure 1 shows that SN 1994I was almost as bright as the nucleus of M51 on April 9.

(b) Data Reduction

The object CCD images were bias-subtracted and flattened to correct the pixel-to-pixel variation of the sensitivity of the CCD chip using the image processing software IRAF. Then we derived the instrumental magnitudes of SN 1994I, a reference star TB 135, and a check star in our CCD images. The positions of these stars are marked in Figure 1. The reference star TB 135 (Thompson & Bryan 1989) is located $70''$ west and $55''$ south of the nucleus of M51. The check star C we used to check the reliability of our photometry is located 228″ east and 78″ south of the nucleus of M51. It is quite straightforward to measure the instrumental magnitudes of the reference star and the check star. However, it is not easy to derive an accurate photometry of SN 1994I from our CCD images, because SN 1994I is located in a spiral arm close to the center of the galaxy where the intensity of the background light varies significantly over a small area. Therefore a simple aperture photometry was not appropriate to measure reliably the brightness of SN 1994I. For this reason, we applied the point-spread function fitting method to SN 1994I using the digital stellar photometry program DAOPHOT II installed in IRAF (Stetson 1992, Davis 1994). We derived the point-spread function from the reference star and the check star, and then fitted it to SN 1994I to derive an instrumental magnitudes of SN 1994I. In estimating the sky brightness for SN 1994I, we used the direct sky estimation method which was suggested for the case of the photometry of stars with varying sky background by Parker (1991).

(c) Calibration

We calibrated the instrumental magnitudes of SN 1994I using the reference star TB 135. $UBVRI$ photometry of TB 135 is given by Corwin (1993). The color terms necessary for the calibration of SN 1994I were derived from the observations of the standard stars in M67 obtained using the same observing system (Chevalier & Ilovaisky 1991, Gilliland *et al.* 1991, Montgomery *et al.* 1993). The resulting color term corrections are very small, because the colors of SN 1994I and TB 135 are similar. Figure 2 displays the photometry of the check star C during the period of our observations. The solid lines represent the mean magnitudes of the check star C. The standard deviations of the mean magnitudes of the check star C are 0.05 mag for U and 0.03 mag for B, V, R and I, showing that our photometry of the check star has been reasonably stable during the observing period. Table 1 summarizes $UBVRI$ CCD photometry of TB 135 and the check star C.

IV. RESULTS

(a) Light Curves of SN 1994I

We list the $UBVRI$ photometry of SN 1994I from April 4 to June 2 in Table 2, and we plot the $UBVRI$ light curves of SN 1994I in Figure 3. We plot also VRI light curves given by Yokoo *et al.* (1994) by crosses for comparison. Figure 3 shows that our VRI photometry is in a reasonably good agreement with that of Yokoo et al. until April 26. However, there is a significant difference between our photometry and Yokoo et al.'s obtained in May. The large difference between ours and Yokoo et al.'s obtained in May appears to be due to the poor quality of our CCD images obtained in poor observing conditions when SN 1994I was getting faint.

The light curves of SN 1994I in Figure 3 show that SN 1994I reaches the maximum brightness at B-band on April 8.23 ($B = 13.68$ mag), at V-band on April 9.10 ($V = 12.89$ mag), and at I-band on April 10.32 ($I = 12.48$ mag). Table 3 lists $UBVRI$ magnitudes of SN 1994I at the maximum brightness which we derived by fitting a combination of a gaussian function and a linear function to the peak area of the light curves. On the other hand, Pooley & Green (1994) found that SN 1994I reaches the maximum brightness at 2cm radio continuum (F(2cm) $= 17.5 \pm 2.0$ mJy) on April 11.18. Thus SN 1994I reaches the maximum brightness later at the longer wavelength. The brightness of SN 1994I declines rapidly after the peak with a declining rate at V of ≈ 0.1 mag/day, and then decreases more slowly after about 20 days from the peak.

There are only a few previously known Type Ic supernovae for which reasonably good light curves are available. SN 1962L in NGC 1073 is the best among them (Bertola 1964, Leibundgut *et al.* 1991). We compared SN 1994I with SN 1962L in Figure 4. We shifted arbitrarily the light curves of SN 1962L along the magnitude axis to match the declining part right after the peak. Figure 4 shows that the shapes of the B and V light curves of SN 1994I obtained in April are very similar to those of SN 1962L. It is also shown that the SN 1994I was ~0.5 mag brighter at U than SN 1962L right before the peak. The similarity between the light curves of SN 1994I and SN 1962L suggests that SN 1994I is of Type Ic.

In Figure 5 we display a comparison of the light curves of SN 1994I and the mean light curves of other types

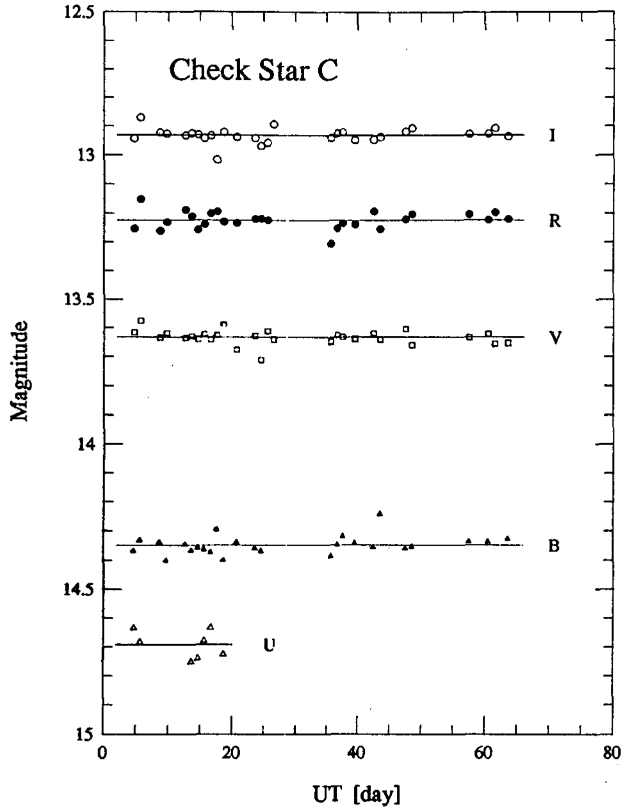

Fig. 2. $UBVRI$ photometry of the check star C

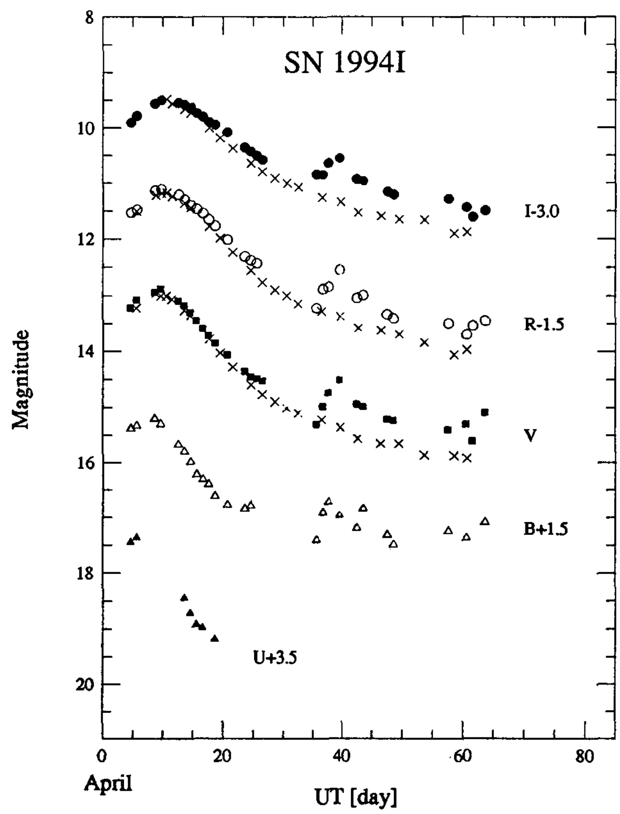

Fig. 3. $UBVRI$ light curves of SN 1994I. The crosses represent the VRI light curves given by Yokoo et al. (1994).

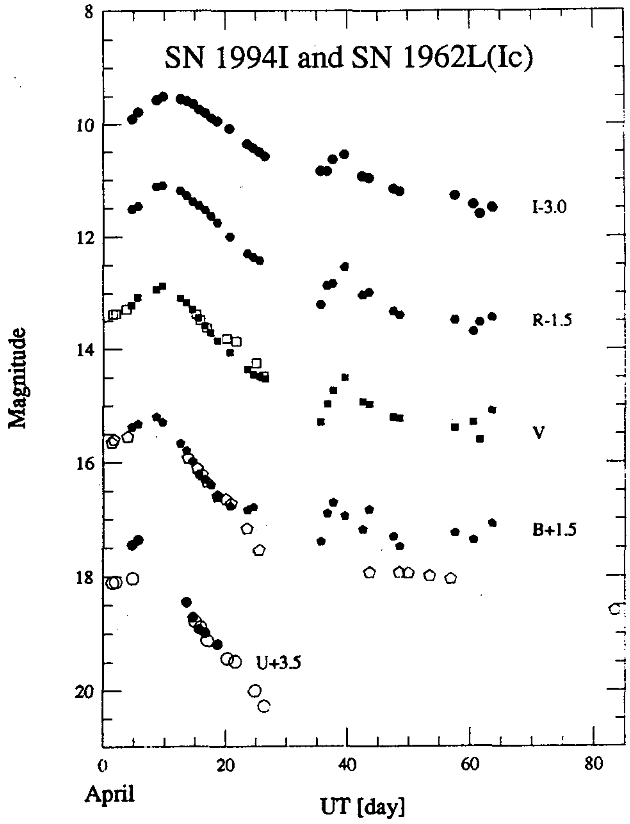

Fig. 4. Comparison of light curves of SN 1994I (filled symbols) and SN 1962L (open symbols).

of supernovae, Ia, II-L, II-P (Dogget & Branch 1985) and Ib (Kirshner 1990). We shifted arbitrarily the mean light curves of other types of supernovae to match the peaks. Figure 5 shows (a) that the light curves around the maximum brightness of SN 1994I are much narrower than those of other types of supernovae, and (b) that the light curves after the peak of SN 1994I decline more steeply compared with those of other types of supernovae.

(b) Color Curves of SN 1994

The color curves of SN 1994I we obtained are displayed in Figure 6. The *VRI* color curves given by Yokoo et al.'s are also plotted by crosses in Figure 6 for comparison. The color curves of ours and Yokoo et al.'s agree in general through the observing period, except for the fact that our photometry shows a little larger scatter than Yokoo et al.'s. Our V, R and I magnitudes obtained in May are systematically brighter than Yokoo et al.'s, but the colors agree reasonably well between the two. Our $(B-V)$ colors are judged to be useful only for the data obtained before April 20.

Figure 6 shows that the colors of SN 1994I get redder from $(V-R) \approx 0.2$ mag ($(V-I) \approx 0.3$ mag, $(B-V) \approx 0.7$ mag) on April 4 to $(V-R) \approx 0.6$ mag ($(V-I) \approx 0.9$ mag, $(B-V) \approx 1.3$ mag) on April 18. Afterwards $(V-R)$ colors get bluer slightly (by $\sim$0.005 mag/day), while $(V-I)$ colors stay almost constant around $(V-I) \approx 1.0$ mag. We also plotted for comparison the mean $(B-V)$ color curve of Type Ia supernovae given by Wheeler & Harkness (1990) in Figure 6. The $(B-V)$ color curve of Type Ia supernovae begins at the point of the maximum brightness of Type Ia supernovae. A comparison of the mean color curves of SN 1994I and Type Ia supernovae shows two major differences. First, the colors of SN 1994I are much redder compared with those of Type Ia supernovae. Secondly, the color gradients of SN 1994I change around 10 days after the maximum brightness, while the color gradient of Type Ia supernovae changes around 40 days after the maximum brightness.

The color at the maximum brightness of SN 1994I is $(B-V) \approx 0.9$ mag ($(V-R) \approx 0.3$ mag, $(V-I) \approx 0.4$ mag), which is $\sim$1 mag redder than the mean color of typical Type Ia supernovae at the maximum brightness. The mean

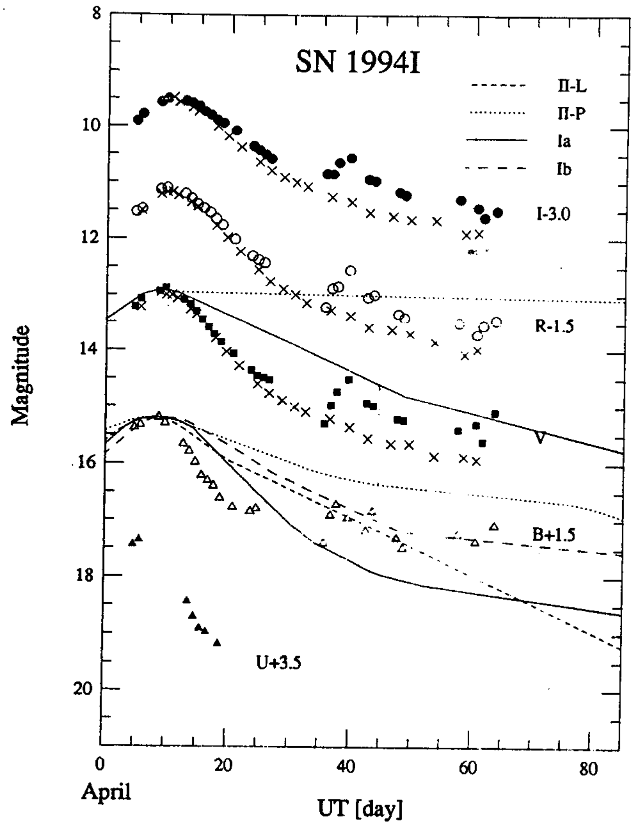

Fig. 5. Comparison of light curves of SN 1994I and other types of supernovae. The crosses represent the VRI light curves given by Yokoo et al. (1994).

intrinsic color of Type Ia supernovae at the maximum brightness has been known to be $(B-V) = -0.3$ to 0.0 mag (Branch & Tammann 1992, van den Bergh & Pierce 1992, Sandage & Tammann 1993, Sandage *et al.* 1994). The mean intrinsic color of the type Ic supernovae at the maximum brightness is not yet known. If it is known, then the reddening for the supernovae can be estimated. For example, if it is similar to that of the type Ia supernovae, the red color of SN 1994I indicates that the reddening for SN 1994I may be as large as $E(B-V) \approx 1$ mag. Since M51 is located at a high galactic latitude of $b = 68.56$ deg, the foreground reddening toward M51 is expected to be negligible, as Burstein & Heiles (1984) gives a value of $E(B-V) = 0.0$ mag. Therefore the reddening estimated from the red color of SN 1994I appears to be entirely due to the interstellar dust in M51, not in our Galaxy. The high reddening value for SN 1994I is not unexpected, because SN 1994I is located in the spiral arm with dust lanes. Studies of the mean intrinsic color of the Type Ic supernovae with a large sample are needed for an accurate estimate of the reddening.

IV. DISCUSSION

(a) The Distance to M51

The distance to M51 is not yet accurately known, although it is a famous galaxy. The values for the distance to M51 used in the literature before the discovery of SN 1994I are based either on the redshift or on the Tully-Fisher relation. The systemic velocity of M51, 573 km/s (the helio-centric velocity = 467 km/s)(Tully 1988), leads to redshift distance estimates of 7.2 Mpc and 11.4 Mpc for the assumed values of the Hubble constant $H_0 = 80$ and 50 km/s, respectively. In *Nearby Galaxies Catalog*, Tully (1988) lists a value for the distance to M51 of 7.7 Mpc (corresponding to a distance modulus of $(m-M)_0 = 29.43$ mag), which is estimated using the Tully-Fisher

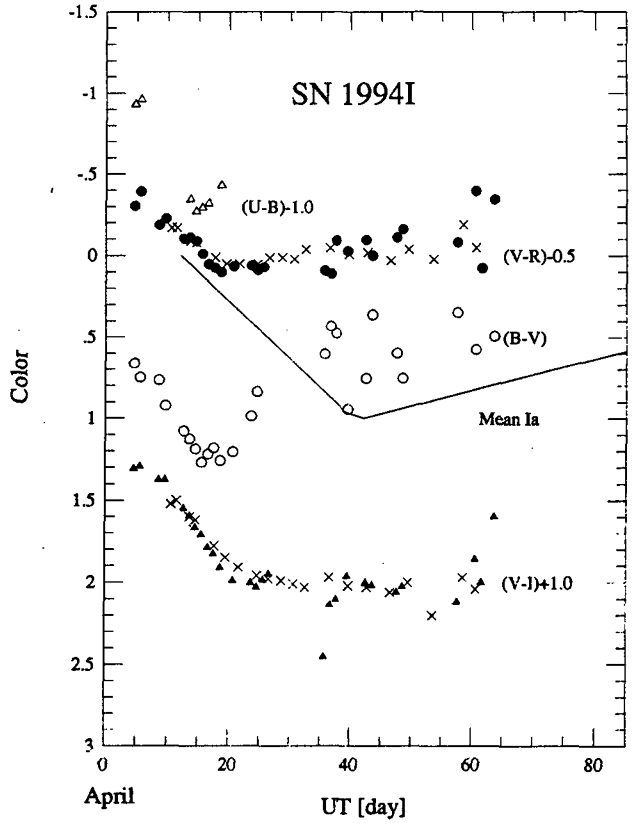

Fig. 6. Color curves of SN 1994I (open triangles: $(U-B)$; filled circles: $(V-R)$; open circles: $(B-V)$; filled trianles : $(V-I)$). The crosses represent the VRI color curves given by Yokoo et al. (1994). The solid line represents the mean $(B-V)$ color curve of Type Ia supernovae.

relation. The values for the parameters he used in his calculations are: the total B magnitude of M51 of $B_T = 8.95$ mag, the inclination angle of 64 deg, the rotational velocity width at 20% level of the peak intensity of $W_{20} = 195$ km/s, the zero foreground extinction, and the internal extinction based on the inclination angle of $A_B = 0.27$ mag. However, the distance estimate for M51 based on the Tully-Fisher relation is subject to some uncertainty, because the inclination angle of M51 is not large enough to yield an accurate distance estimate using the Tully-Fisher relation.

After the discovery of SN 1994I, a new distance estimate for M51 based on the modeling of SN 1994 was given by Iwamoto *et al.* (1994). They fitted the observed light curves of SN 1994I to their theoretical models and derived a value for the distance modulus of $(m-M)_0 = 29.2 \pm 0.3$ mag (6.92 Mpc) and a high extinction value for SN 1994I of $A_V = 1.4$ mag ($E(B-V) = 0.45$ mag). However, the accuracy of this method is not yet tested externally.

Independent estimates of the distance to M51 are needed to confirm these results and investigate the properties of SN 1994I. The distance to M51 can be measured accurately (within 10% error) with Cepheids or the tip of the red giant branch which are observed using the Hubble Space Telescope (Lee, Freedman & Madore 1993). The tip of the red giant branch method can be applied much more easily than the Cepheid method, because the former requires much less observing time than the latter.

(b) Properties of Type Ic supernovae

The class of Type Ic was introduced by Wheeler & Harkness (1986a,b) to distinguish supernovae without any features of H, He and Si in the spectra obtained at the maximum brightness, from Type Ib which is characterized by rich He features without H and Si features. SN 1983V in NGC 1365 was a proto-type for Type Ic. Some of the old Type Ib supernovae were reclassified as Type Ic later (see Wheeler & Harkness 1990). Type Ic supernovae are very rare compared with other types of supernovae. To date there are only eleven supernovae which were classified as

Table 2. *UBVRI* **Photometry of SN 1994I**

UT[a]	HJD[b]	U	B	V	R	I	U-B	B-V	V-R	V-I	n(U)	n(B)	n(V)	n(R)	n(I)
4.681	47.184	13.95	13.88	13.22	13.02	12.91	0.07	0.66	0.20	0.31	1	11	12	11	9
		0.06	0.01	0.01	0.01	0.03	0.06	0.02	0.02	0.03					
5.637	48.140	13.87	13.83	13.08	12.97	12.78	0.04	0.75	0.11	0.30	2	7	5	5	12
		0.03	0.01	0.02	0.01	0.01	0.04	0.03	0.03	0.02					
8.652	51.155		13.70	12.94	12.63	12.56		0.76	0.31	0.38		11	9	9	10
			0.01	0.01	0.04	0.02		0.02	0.04	0.02					
9.675	52.178		13.80	12.88	12.60	12.50		0.92	0.27	0.38		6	3	5	4
			0.02	0.00	0.01	0.01		0.02	0.01	0.01					
12.610	55.114		14.17	13.09	12.70	12.54		1.08	0.40	0.55		10	11	9	9
			0.01	0.01	0.00	0.00		0.01	0.01	0.01					
13.603	56.106	14.95	14.30	13.17	12.78	12.58	0.65	1.12	0.39	0.60	4	8	9	12	11
		0.04	0.01	0.02	0.02	0.02	0.04	0.02	0.02	0.03					
14.615	57.118	15.21	14.48	13.30	12.89	12.63	0.73	1.19	0.41	0.67	4	7	7	8	8
		0.10	0.00	0.01	0.01	0.01	0.10	0.01	0.02	0.02					
15.618	58.121	15.42	14.72	13.45	12.96	12.73	0.70	1.27	0.49	0.71	4	4	8	7	6
		0.08	0.01	0.01	0.00	0.00	0.08	0.02	0.01	0.01					
16.643	59.146	15.48	14.81	13.59	13.04	12.80	0.68	1.22	0.55	0.79	4	12	12	13	12
		0.06	0.02	0.01	0.00	0.01	0.06	0.02	0.01	0.01					
17.592	60.095		14.90	13.72	13.14	12.89		1.18	0.57	0.83		4	4	4	2
			0.02	0.01	0.02	0.01		0.02	0.02	0.01					
18.653	61.156	15.69	15.12	13.86	13.26	12.94	0.57	1.26	0.60	0.91	5	8	11	12	11
		0.03	0.02	0.01	0.01	0.01	0.03	0.02	0.01	0.01					
20.712	63.215		15.28	14.07	13.51	13.08		1.20	0.57	0.99		7	7	9	9
			0.01	0.01	0.02	0.02		0.02	0.03	0.02					
23.587	66.090		15.35	14.36	13.80	13.36		0.99	0.56	1.01		8	10	11	12
			0.03	0.03	0.03	0.03		0.04	0.04	0.04					
24.547	67.050		15.30	14.46	13.87	13.43		0.84	0.59	1.03		5	7	8	8
			0.01	0.04	0.02	0.02		0.04	0.04	0.04					
25.563	68.066			14.49	13.92	13.50			0.57	0.99			7	8	8
				0.02	0.04	0.02			0.04	0.03					
26.515	69.018			14.53		13.58				0.95			6		1
				0.02		0.012				0.02					
35.646	78.149		15.90	15.30	14.71	13.84		0.60	0.59	1.46		2	4	5	5
			0.08	0.08	0.09	0.04		0.12	0.12	0.09					
36.696	79.198		15.41	14.98	14.37	13.85		0.43	0.61	1.14		7	6	7	6
			0.07	0.06	0.03	0.04		0.10	0.07	0.07					
37.618	80.120		15.22	14.75	14.34	13.64		0.47	0.41	1.11		3	3	6	3
			0.05	0.05	0.06	0.03		0.07	0.08	0.06					
39.559	82.061		15.46	14.52	14.05	13.55		0.94	0.47	0.96		3	3	3	3
			0.06	0.04	0.04	0.08		0.07	0.06	0.09					
42.525	85.027		15.69	14.94	14.54	13.94		0.75	0.40	1.01		4	5	4	4
			0.02	0.02	0.06	0.05		0.03	0.07	0.06					
43.560	86.062		15.35	14.99	14.49	13.97		0.36	0.50	1.02		3	5	4	4
			0.05	0.05	0.03	0.05		0.07	0.06	0.07					
47.549	90.051		15.82	15.22	14.83	14.16		0.60	0.39	1.06		2	7	4	4
			0.03	0.04	0.03	0.03		0.04	0.05	0.05					
48.553	91.054		15.99	15.24	14.90	14.21		0.75	0.34	1.03		3	7	4	4
			0.02	0.03	0.05	0.07		0.04	0.06	0.07					
57.565	100.066		15.75	15.41	14.99	14.29		0.34	0.42	1.12		3	4	3	4
			0.02	0.03	0.07	0.05		0.04	0.07	0.06					
60.557	103.058		15.87	15.30	15.20	14.44		0.57	0.10	0.86		3	3	5	4
			0.02	0.08	0.06	0.03		0.08	0.10	0.09					
61.581	104.082			15.61	15.03	14.61			0.58	1.00			4	4	3
				0.03	0.03	0.01			0.05	0.04					
63.615	106.116		15.59	15.10	14.94	14.50		0.49	0.16	0.60		1	3	5	4
			0.18	0.02	0.07	0.06		0.18	0.07	0.06					

[a] UT[day] starts at the beginning of April 1, 1994.

[b] HJD means HJD-2449400.

NOTE. —Every second line represents photometric errors.

Table 3. *Maximum Brightness of SN 1994I*

Filter	Mag(max)	UT–April 0[day]
U	13.80	6.50
B	13.68	8.23
V	12.89	9.10
R	12.58	9.72
I	12.48	10.32

Table 4. *A List of Known Type Ic Supernovae*

SN	Galaxy	Type	v(km/s)	$(m-M)_0$	Mag(dis)
1962L	NGC 1073	SB(rs)c	1212	30.91	B 15.2
1964L	NGC 3938	SA(rs)bs	805	31.15	B 13.5
1983I	NGC 4051	SAB(rs)bc	710	31.15	B 15.0
1983V	NGC 1365	SB(s)b	1639	31.14	
1987M	NGC 2715	SAB(rs)c	1126	31.55	B 15.0
1988L	NGC 5480	SA(s)c	1907	32.52	
1990U	NGC 7479	SBbcI-II	2394	32.55	B 16.0
1990W	NGC 6221	SbcII-III	1350	31.44	V 15.0
1991A	IC 2973	SBd:	3199	33.46[a]	B 17.0
1992ar	anonymous		40000	38.95[a]	B 19.0
1994I	M51	SbcI-II	463	29.2	V 13.5

[a]Based on the Hubble constant of 65 km s^{-1} Mpc^{-1}.

obvious Type Ic supernovae, as listed in Table 4. The data in Table 4 were drawn from Wheeler & Harkness (1990) and a catalog of recent supernovae by van den Bergh (1994). The last column lists the magnitudes of discovery and the colors of discovery magnitude. Table 4 shows that all Type Ic supernovae were discovered in spiral galaxies of late type (subclasses b or later). SN 1994I is the nearest among them. There were only a few previously known Type Ic supernovae of which reasonably good photometry are available before the discovery of SN 1994I. However, there was no previous Type Ic supernova of which photometry is complete enough to cover the light curves before, during and after the maximum brightness. SN 1994I provides us, for the first time, with an opportunity to investigate the light curves of Type Ic supernovae in detail, as was described in the previous section.

Adopting the distance modulus of $(m - M)_0 = 29.2$ mag and a value for the extinction of $A_V = 1.5$ mag as estimated by Iwamoto *et al.* (1994), we derive absolute magnitudes at the maximum brightness of SN 1994I, $M_V(\max) = -17.7$ mag and $M_B(\max) = -17.4$ mag. This result shows that SN 1994I was $\sim$2 mag fainter at the maximum brightness compared with Type Ia supernovae for which the maximum brightness is known to be $M_V \approx M_B \approx -19.6$ mag (Sandage *et al.* 1994). In general, Type Ib and Ic supernovae have been known to be ≈ 1.5 mag fainter than Type Ia supernovae (Wheeler & Harkness 1990).

(c) Progenitors of SN 1994I

Two contrasting models have been suggested for explaining the progenitors of Type Ic supernovae. One is a massive Wolf-Rayet star model where a massive star loses its H and He envelope in a strong stellar wind to become a Wolf-Rayet star, and the other is a low mass binary star model where a star in a close binary system loses its H and He envelope via Roche-lobe outflow to its companion star (see the references in Wheeler & Harkness 1990; Nomoto *et al.* 1994a,b). SN 1994I provides an ideal laboratory to test these models.

A narrower peak and faster decline after the maximum in the light curve of SN 1994I compared with other types of supernovae indicate that the progenitor of SN 1994I might be a lower mass star compared with those of other types of supernovae. This supports the low mass binary star models for the Type Ic supernovae rather than the massive Wolf-Rayet star models. Detailed theoretical modelings of Type Ic supernovae including SN 1994I were recently given by Nomoto and his collaborators (Nomoto *et al.* 1994a,b; Iwamoto *et al.* 1994). They presented, as a model for the progenitor of SN 1994I, a carbon-oxygen star model. According to their models, a main-sequence star of mass $13 - 15 M_\odot$ in a close binary system loses first its H-rich envelope and then its He envelope (as a result, the spectra of Type Ic supernovae do not show any feature of H and He) to eventually become a bare carbon-oxygen star of mass $\sim 2\ M_\odot$ which is exploded by iron core collapse.

V. SUMMARY AND CONCLUSIONS

We presented *UBVRI* CCD photometry of SN 1994I obtained for the first two months since the discovery of SN 1994I. The primary results obtained in this study are summarized as follows.

1. SN 1994I reaches the maximum brightness at B-band on April 8.23 ($B = 13.68$ mag), at V-band on April 9.10 ($V = 12.89$ mag), and at I-band on April 10.32 ($I = 12.48$ mag).
2. The light curves of SN 1994I are similar to those of the Type Ic supernova SN 1962L in NGC 1073.
3. The light curves around the maximum brightness are much narrower than those of other types of supernovae.
4. The light curves after the peak decline more steeply compared with those of other types of supernovae.
5. The colors get redder from $(V - R) \approx 0.2$ mag ($(V - I) \approx 0.3$ mag, $(B - V) \approx 0.7$ mag) on April 4 to $(V - R) \approx 0.6$ mag ($(V - I) \approx 0.9$ mag, $(B - V) \approx 1.3$ mag) on April 18. Afterwards $(V - R)$ colors get bluer slightly (by ~ 0.005 mag/day), while $(V - I)$ colors stay almost constant around $(V - I) \approx 1.0$ mag. The color at the maximum brightness is $(B - V) = 0.9$ mag, which is $\sim$1 mag redder than the mean color of typical Type Ia supernovae at the maximum brightness.
6. Adopting the distance modulus of $(m - M)_0 = 29.2$ mag and a value for the reddening of $E(B - V) = 0.45$ mag for SN 1994I, we derive absolute magnitudes at the maximum brightness of SN 1994I, $M_V(\max) = -17.7$ mag and $M_B(\max) = -17.4$ mag, showing that SN 1994I was $\sim$2 mag fainter at the maximum brightness compared with Type Ia supernovae.

7. A narrower peak and faster decline after the maximum in the light curve of SN 1994I compared with other types of supernovae indicate that the progenitor of SN 1994I might be a lower mass star compared with the progenitors of other types of supernovae.

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