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THE PROGENITOR OF SN 2004dj IN A STAR CLUSTER

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ABSTRACT

The progenitor of Type II-P (P = plateau) supernova SN 2004dj is identified with a supergiant in a compact star cluster known as "Sandage's star 96" (S96) in the nearby spiral galaxy NGC 2403, which was fortuitously imaged as part of the Beijing-Arizona-Taiwan-Connecticut (BATC) Multicolor Sky Survey from 1995 February to 2003 December prior to SN 2004dj. The superior photometry of BATC images for S96, taken with 14 intermediate-band filters covering 3000–10000 Å, unambiguously establishes the star cluster nature of S96, with an age of ∼20 Myr, a reddening of $E(B-V) \sim 0.35$ mag, and a total mass of ∼96,000 $M_{\odot}$. The compact star cluster nature of S96 is also consistent with the lack of light variations in the past decade. The SN progenitor is estimated to have a main-sequence mass of ∼12 $M_{\odot}$. The comparison of our intermediate-band data of S96 with the postoutburst photometry obtained as the SN significantly dims with time may hopefully conclusively establish the nature of the progenitor.

Subject headings: galaxies: individual (NGC 2403) — galaxies: star clusters — stars: evolution — supergiants — supernovae: general — supernovae: individual (SN 2004dj)

1. INTRODUCTION

Identification of the progenitors of supernovae (SNe) is extremely valuable for testing theories of stellar evolution and SN explosions. Type II SNe arise from core collapses of evolved massive stars (Paczyński 1971; Goldreich & Weber 1980). The subclass of Type II-P (P = plateau) SNe is thought to be associated with red supergiants of higher initial masses that retained their hydrogen envelopes before core collapse. This model accounts for the main observed features (spectra and light curves) and the estimated physical parameters of the expanding photosphere, such as velocity, temperature, and density (Woosley & Weaver 1986; Hamuy 2003). However, there is little direct evidence for the red supergiant hypothesis. To date, only three SNe have had their progenitors identified: SN 1987A (Gilmozzi et al. 1987; Sonneborn et al. 1987), SN 1993J (Aldering et al. 1994; Maund et al. 2004), and SN 2003gd (Van Dyk et al. 2003; Smartt et al. 2004). The progenitor of the peculiar Type II SN 1987A was a blue supergiant. The Type IIb SN 1993J arose in a massive interacting binary. The progenitor of Type II-P SN 2004et in NGC 6946 was tentatively identified as a yellow supergiant (Li et al. 2005). Thus, the expected red supergiant origin for the common Type II-P SNe is only favored for SN 2003gd. The fortuitous occurrence of Type II-P SN 2004dj in a nearby galaxy with prediscovery images has allowed us to examine its progenitor.

SN 2004dj was discovered on 2004 July 31.76 UT by K. Itagaki (Nakano 2004) in the nearby spiral galaxy NGC 2403 about 3.3 Mpc away (Karachentsev et al. 2004). Initially, the reported *V*-band magnitude was ∼11.2 mag, making SN 2004dj the optically brightest SN in the past decade since SN 1993J in M81. The initial spectrum of SN 2004dj resembles that of a normal Type II-P supernova, with prominent P Cygni profiles in hydrogen Balmer lines (Patat et al. 2004).

Through astrometric registration of archival images of NGC 2403 and recent images of SN 2004dj, Maíz-Apellániz et al. (2004, hereafter MA04) established that SN 2004dj coincided with Sandage's star 96 (S96) in the list of luminous stars and clusters in NGC 2403 (Sandage 1984). Using the earlier photometry of S96 (Larsen 1999), MA04 suggested that S96 was a young compact cluster with an age of 13.6 Myr and a total stellar mass of 24,000 $M_{\odot}$. They inferred that the progenitor of SN 2004dj had a main-sequence mass of ∼15 $M_{\odot}$.

In this Letter, we identify the progenitor of SN 2004dj by combining recent and archival images from the Beijing-Arizona-Taiwan-Connecticut (BATC) Sky Survey. We find that the spectral energy distribution (SED) of S96 resembles that of a star cluster rather than a single star. Using the simple stellar population (SSP) model, we reexamine the age and mass of S96 and set new limits on the progenitor mass of SN 2004dj.

2. BATC OBSERVATIONS OF S96

2.1. *Archival Images of the BATC Sky Survey*

The observations of NGC 2403 were obtained by the BATC 60/90 cm Schmidt telescope located at the Xinglong station of the National Astronomical Observatory of China (NAOC). This telescope has 15 intermediate-band filters covering the optical wavelength range of 3000–10000 Å and is specifically designed to avoid contaminations from the brightest and most variable night-sky emission lines. Descriptions of the BATC photometric system can be found in Fan et al. (1996).

Figure 1 compares the pre- and postexplosion images of SN 2004dj. The left panel shows the field of SN 2004dj and neighboring bright field stars, as imaged in the *i* band (centered at 6656 Å) of the BATC system with the NAOC 60/90 cm Schmidt telescope on 2004 August 11. In the right panel, we show the same field, as extracted from the BATC *i*-band images taken on 1995 December 20. SN 2004dj coincides with S96

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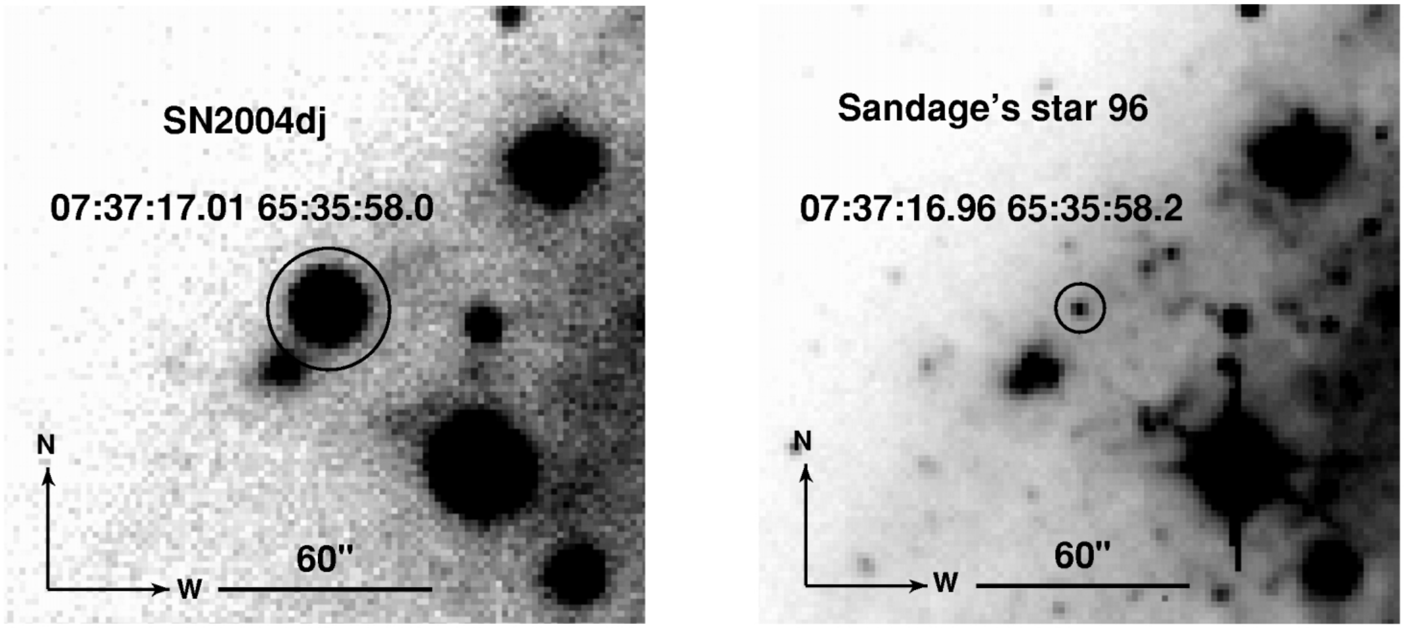

FIG. 1.—*Left*: Image of SN 2004dj in the BATC *i* band of the NAOC 60/90 cm Schmidt telescope on 2004 August 11. The SN is circled. *Right*: Same field, but observed before SN 2004dj on 1995 December 20. The SN is found to coincide with Sandage's star 96 (*circled*). The field of view for both images is 3′ × 3′.

to within 0″.7 based on the astrometry measurements of these two images.

We extracted 213 images of NGC 2403, taken in 14 BATC filters, except for the *b* filter, from the BATC survey archive during 1995 February–2003 December. Table 1 contains the log of observations. Multiple images of the same filter were combined to improve the image quality, assuming a nonvariable S96. These serendipitous data provide a unique opportunity to examine the properties of pre-SN S96.

2.2. *Intermediate-Band Photometry of S96*

S96 is located in a somewhat complex background involving a spiral arm and possibly surrounding H II regions. To obtain proper photometry, we need to consider the flux contribution from the host galaxy background underneath S96. We invoked a method that assumes that the spiral plane around S96 is stable, that satisfies the Laplace equation, and that solves for the flux distribution of the spiral arm at the position of S96 (Zhang et al. 2004). The pure flux of S96 can then be estimated by subtracting the host galaxy contribution from the total flux.

The final magnitudes of S96 are determined by the subtracted images using standard aperture photometry. The BATC photometric system calibrates the magnitude zero level similar to the spectrophotometric AB magnitude system. For the flux calibration, the Oke-Gunn primary flux standard stars HD 19445, HD 84937, BD +26°2606, and BD +17°4708 were observed during photometric nights (Yan et al. 2000). The results of the well-calibrated photometry of S96 in 14 filters are summarized in the fifth column of Table 1. These intermediate-band magnitudes (see Fig. 3 below) agree well with the broadband *UBVI* magnitudes measured by Larsen (1999).

The numerous BATC images of NGC 2403 (Table 1) allow us to examine the variability of S96 in the past decade, which will shed light on the nature of the object. For example, significant light variations are expected on a timescale of a few years, if S96 was a luminous blue supergiant (Humphrey & Davidson 1994). We converted all BATC magnitudes, measured at different epochs and with higher qualities, into the *i* band by utilizing the color of S96 inferred from Table 1. As shown in Figure 2, the composite *i*-band light curve of S96 in the past decade does not show significant luminosity variations, and most of the data are within ± 0.13 mag (1 σ) of the average value. The fit for a flat light curve gives $\chi^2 = 49$ for 43 data points. This also justifies that the image combination employed in our data reduction is reasonable.

TABLE 1
BATC PHOTOMETRY OF SANDAGE'S STAR 96

Filter	λ (Å)	FWHM (Å)	N[a]	Value (mag)	Time Span
a ……	3360	360	8	18.73(0.24)	1998 Dec
c …….	4210	320	8	18.18(0.04)	1998 Dec–2003 Nov
d ……	4540	340	38	18.16(0.03)	1998 Dec–2003 Nov
e …….	4925	390	17	18.12(0.07)	1995 Mar–2003 Jan
f …….	5270	340	9	18.12(0.05)	1995 Feb–Dec
g ……	5795	310	13	17.93(0.04)	1995 Feb–1996 Jan
h ……	6075	310	12	17.85(0.06)	1995 Feb–1996 Jan
i …….	6656	480	11	17.78(0.06)	1995 Feb–1999 Jan
j …….	7057	300	10	17.61(0.09)	1995 Feb–2003 Dec
k …….	7546	330	13	17.57(0.06)	1995 Feb–1996 Mar
m ……	8023	260	17	17.57(0.08)	1995 Feb–2003 Dec
n ……	8480	180	17	17.51(0.18)	1995 Feb–2000 Oct
o ……	9182	260	17	17.45(0.11)	1995 Feb–2003 Dec
p ……	9739	270	23	17.42(0.25)	1995 Feb–2000 Feb

[a] The number of images taken by the BATC telescope.

3. STELLAR POPULATION OF S96

3.1. *Stellar Populations and Synthetic Photometry*

To probe the nature of S96, we compare its SED with theoretical stellar population synthesis models. We explore two different SED families, one for single stars and the other for cluster populations. For stellar models, we used the theoretical stellar spectral flux library of Lejeune et al. (1997). For cluster spectra, we used the SSP models (e.g., Bruzual & Charlot 2003, hereafter BC03).

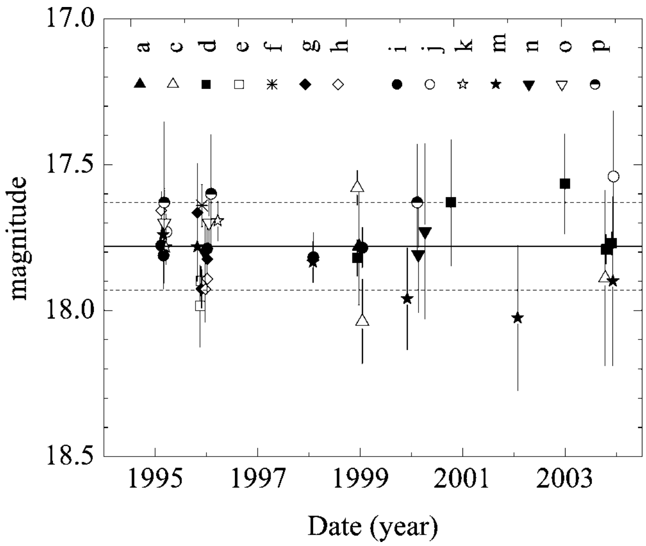

FIG. 2.—Composite *i*-band light curve of S96. The filled circles show the *i* band magnitudes, and other symbols show those magnitudes converted from the other 13 bands. All BATC band symbols are labeled on top. The solid line is the mean value of the *i*-band magnitudes, and the two horizontal dashed lines mark the $\pm 1\ \sigma$ error.

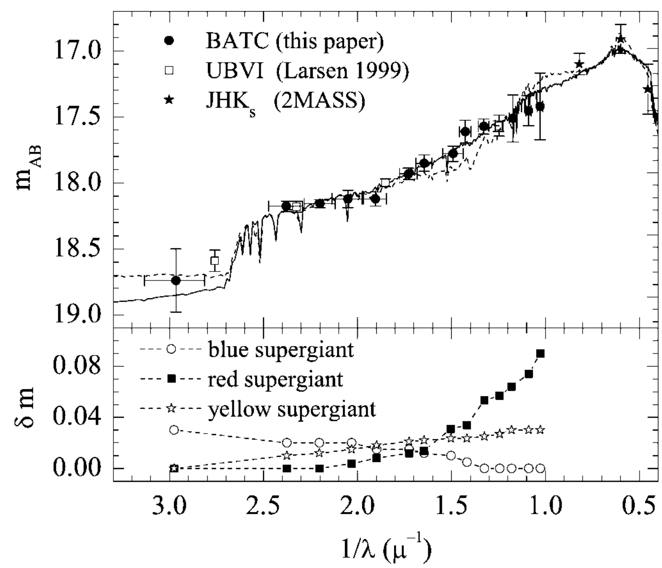

FIG. 3.—*Upper panel*: Best-fit SED (20 Myr solution) for S96, overlaid with that obtained by MA04 (*dashed line*). The photometric points are shown with error bars (vertical ones for uncertainties and horizontal ones for the FWHM of BATC filter). *Lower panel*: Predicted flux drops of S96 when the SN has faded away.

We convolve the SEDs of single stars from Lejeune et al. (1997) and of stellar clusters from BC03 with the BATC filter transmission curves to obtain synthesized optical and near-infrared photometry for comparisons. The synthetic *i*th BATC filter magnitude can be computed by

$$m = -2.5 \log \frac{\int_\lambda F_\lambda \varphi_i(\lambda) d\lambda}{\int_\lambda \varphi_i(\lambda) d\lambda} - 48.60, \qquad (1)$$

where F_λ is the SED from the library and φ_i is the transmission function of the *i*th filter of the BATC photometric system. Here, F_λ varies with temperature and metallicity for stellar models, and with age and metallicity for star clusters. We explore the nature of S96 by fitting the observed SED with distinct theoretical models.

3.2. *Reddening and Metallicity of S96*

To obtain the intrinsic SED of S96, the photometry must be dereddened. The Na I D interstellar absorption lines can provide clues to the reddening. However, the two reports about the measurements of these feature lines of SN 2004dj (Patat et al. 2004; Guenther & Klose 2004) show larger differences. As a result, we treat $E(B-V)$ as a fitting parameter. The values of extinction coefficient R_λ for the BATC filters are obtained by interpolating the extinction curve of Cardelli et al. (1989).

The SEDs for clusters or single stars are significantly affected by the adopted metallicity. Garnett et al. (1997) measured the metallicity and its radial gradient in NGC 2403. S96 is 160″ east and 10″ north of the galactic nucleus of NGC 2403, or at 4.0 kpc from the galactic center when removing the projection effect. At this radial distance, the relative oxygen abundance log (O/H) + 12 is 8.45 ± 0.10 dex from Garnett et al., which is ~40% of the solar value. We then adopt a subsolar metallicity of $z = 0.008$ for S96 in the analysis.

3.3. *Fitting Results*

We use the χ^2 test to examine which members of the SED families are most compatible with the observed one. We show in Figure 3 the observed integrated photometry of S96 and the best-fit SED model.

Our fitting results do not favor S96 as a single luminous star. Fitting the BATC photometry for the stellar model yields the solution of a highly reddened [$E(B-V) = 0.78 \pm 0.05$ mag] B2 IV star, but its best-fit χ^2 is 24 for 14 BATC points (with 12 degrees of freedom), indicating a rather poor quality of the fit. There are another three reasons why this fit does not work for S96: (1) the corrected intrinsic $B-V$ color is too blue to be consistent with a B-type star; (2) such an extremely blue and bright star is most likely a luminous blue variable, but it did not show significant light variations (see Fig. 2); and (3) the high reddening would imply an unrealistically high luminosity, $M_V \lesssim -18.9$ mag at the maximum light, for SN 2004dj as a Type II-P event (e.g., Hamuy 2003).

In comparison, the star cluster models provide better fits to the observed SED of S96. The best reduced χ^2 of 0.76 is achieved for a cluster model with an age of 19.1 ± 3.3 Myr and a reddening of $E(B-V) = 0.34 \pm 0.05$ mag. When the Two Micron All Sky Survey (2MASS) infrared JHK_s data (Skrutskie et al. 1997) are included in the fit, the best-fit parameters for S96 are a cluster age of 20.0 ± 3.4 Myr and a reddening of $E(B-V) = 0.35 \pm 0.05$ mag with a similarly small reduced χ^2 of 0.77. The uncertainties (1 σ) in age and reddening are derived from the likelihood map that was restricted by the χ^2 distribution in the age-extinction plane. We reproduce in Figure 3 the SED based on the parameters derived by MA04 (*dashed curve*), which does not fit well the BATC data (especially in the *i*, *j*, and *k* bands) since the best fit gives $\chi^2 = 19$ for 14 points.

Adopting these age and extinction estimates, we determine the total mass of the stellar population from the distance to NGC 2403 and the measured *V* magnitudes (transformed from observed magnitudes in the BATC bands). We inferred the total mass of ~96,000 $M_\odot$ by comparing the measured *V*-band luminosity with the theoretical mass-to-light ratios (BC03). The turnoff mass is ~12 $M_\odot$ for a cluster age of 20 Myr. The parameters estimated for S96 are listed in Table 2.

TABLE 2
FITTING PARAMETERS FOR SANDAGE'S STAR 96

Parameter	BATC	BATC+JHK_s
Age (Myr)	19.1 ± 3.3	20.0 ± 3.4
$E(B-V)$ (mag)	0.34 ± 0.05	0.35 ± 0.05
Mass ($10^3\ M_\odot$)	93.5 ± 14.8	96.2 ± 15.3
Reduced χ^2	0.76	0.77
Turnoff mass ($M_\odot$)	12.2	11.7

4. DISCUSSION AND CONCLUSIONS

MA04 estimated a younger age of ∼13.6 Myr and a lower reddening[6] of $E(B-V) = 0.17$ mag for S96, using the broadband *UBVI* photometry of Larsen (1999). Our results differ from those of MA04 at a confidence level of ∼2 σ, which is primarily caused by the differences in metallicity and spectral coverage. Given a lower metallicity of $z = 0.008$ for S96, however, the combination of *UBVI* and JHK_s photometry yields two solutions in the age-reddening plane. The solution of an older age of ∼19 Myr with a reduced χ^2 of 0.89 is similar to ours, while the solution of a younger age of ∼10 Myr is equally compelling and cannot be rejected due to a smaller χ^2 of 1.02. The occurrence of multiple solutions may be related to the lower spectral resolution of the broadband photometry. In comparison, the BATC data constrain the SED better. For instance, our *i*-band photometry could indicate that S96 was not an Hα-bright source, and hence the younger age solution is unlikely, but the existing *UBVI* data alone fail to do that. The effect of different SED models on the results may be small as suggested by de Grijs et al. (2005). This is manifest in our data analysis of S96 using both BC03 and Starburst99 models (Leitherer et al. 1999). At a fixed metallicity, the age difference derived from these two models is within 2–3 Myr, and the extinction difference is within 0.06 mag.

While the observed SED of S96 resembles that of a star cluster, several photometric points shown in Figure 3 do not fit well, e.g., the *f* and *j* bands. This small deviation of ∼0.1 mag from the best-fit SED may be caused by the model uncertainties, the photometric errors, or even flux modulations of the immediate progenitor star. In the last case, we set limits on the possible variability. Given the luminosity of S96 and the luminosity predicted from the supergiant with a main-sequence mass of 12 $M_\odot$, we estimate that the flux contribution of the progenitor is 3%–8% of the whole cluster, depending on the supergiant types. By relegating all scatters (∼0.13 mag) shown in Figure 2 to the progenitor itself, we place a rather crude upper limit of ∼1.5 mag on its light variation.

The progenitor mass of SN 2004dj inferred in S96 (∼12 $M_\odot$) is within the mass range found for other Type II-P SNe (Leonard et al. 2002; Van Dyk et al. 2003; Smartt et al. 2003, 2004). While it remains uncertain whether the progenitor of SN 2004dj was a blue, yellow, or red supergiant in the compact cluster S96, a comparison of flux changes for pre- and postoutburst phases of S96 in the blue and red bands may offer us key clues to distinguish the various scenarios. Given a blue or yellow supergiant, the post-SN flux of S96 would change by ∼0.02–0.03 mag (Fig. 3). If the progenitor was a red supergiant, the flux drop of S96 at NIR bands from *k* to *p* would reach ∼0.07 mag. This change might be detectable by scrutinizing S96, preferably with the *Hubble Space Telescope*, when the supernova becomes significantly dimmed several years from now (Zhang et al. 2004).

We conclude that SN 2004dj occurred in the young compact star cluster S96 of age ∼20 Myr. The lack of light variations in S96 supports this cluster identification. The progenitor of SN 2004dj is inferred to be a supergiant with a main-sequence mass of ∼12 $M_\odot$. Post-SN observations of S96 and detailed photometric and spectroscopic studies of the SN evolution may further constrain the progenitor of SN 2004dj.

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[6] There is also a solution for an older age of 28.8 Myr and a larger reddening of $E(B-V) = 0.28$ mag with a reduced χ^2 of ∼1.74 in their analysis, but it is considered less likely.