THE PROGENITOR OF SN 2004dj IN A STAR CLUSTER

Xiaofeng Wang,1,2 Yanbin Yang,1 Tianmeng Zhang,1 Jun Ma,1 Xu Zhou,1 Weidong Li,3 Yu-Qing Lou,1,2,4 and Zongwei Li4

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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) ~ 0.35 mag, and a total mass of ~96,000 M⊙. 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⊙. 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 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, Maiz-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⊙. They inferred that the progenitor of SN 2004dj had a main-sequence mass of ~15 M⊙.

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
to within 0\textdegree 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\degree 2606, and BD +17\degree 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 $\pm 0.13$ mag (1\sigma) 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.

### 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).
families are most compatible with the observed one. We show
of for S96 in the analysis.

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
ith BATC filter magnitude can be computed by

\[ m = -2.5 \log \int \frac{F_\lambda \varphi_i(\lambda) d\lambda}{\int \varphi_i(\lambda) d\lambda} - 48.60, \]  

(1)

where \( F_\lambda \) is the SED from the library and \( \varphi_i \) is the transmission
function of the ith filter of the BATC photometric system. Here, \( F_\lambda \) 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 the-
oretical 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 \( R_V \) 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 \( \chi^2 \) 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 \( \chi^2 \) 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, \( M_V \approx -18.9 \) 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 \( \chi^2 \) 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 data
(Skrutskie et al. 1997) are included in the fit, the best-fit pa-
rameters 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 \( \chi^2 \) of 0.77. The uncertainties (1 \( \sigma \)) in age and
reddening are derived from the likelihood map that was re-
stricted by the \( \chi^2 \) 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 \( \sim 96,000 M_\odot \) by comparing the measured \( V \)-band lu-
minosity with the theoretical mass-to-light ratios (BC03). The
turnoff mass is \( \sim 12 M_\odot \) for a cluster age of 20 Myr. The
parameters estimated for S96 are listed in Table 2.
4. DISCUSSION AND CONCLUSIONS

MA04 estimated a younger age of \( \sim 13.6 \) 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 \( \sim 2 \sigma \), 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 photometry yields two solutions in the age-reddening plane. The solution of an older age of \( \sim 19 \) Myr with a reduced \( \chi^2 \) of 0.89 is similar to ours, while the solution of a younger age of \( \sim 10 \) Myr is equally compelling and cannot be rejected due to a smaller \( \chi^2 \) 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 H\(_\alpha\)-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 \( \sim 0.1 \) 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 (\( \sim 0.13 \) mag) shown in Figure 2 to the progenitor itself, we place a rather crude upper limit of \( \sim 1.5 \) mag on its light variation.

The progenitor mass of SN 2004dj inferred in S96 (\( \sim 12 M_\odot \)) 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 \( \sim 0.02-0.03 \) mag (Fig. 3). If the progenitor was a red supergiant, the flux drop of S96 at NIR bands from \( k \) to \( p \) would reach \( \sim 0.07 \) mag. This change might be detectable by scrutinizing S96, preferably with the \textit{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 \( \sim 20 \) 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 \( \sim 12 M_\odot \). 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 \( \chi^2 \) of \( \sim 1.74 \) in their analysis, but it is considered less likely.