THE PROGENITOR OF THE TYPE II-P SN 2004dj IN NGC 2403

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ABSTRACT

The Type II-P supernova SN 2004dj in the nearby galaxy NGC 2403 occurred at a position coincident with object 96 in the list of luminous stars and clusters in this galaxy published by Sandage in 1984. The coincidence is established definitively through astrometric registration of our ground-based archival images of NGC 2403 with our recent images showing the SN. The archival images show that Sandage 96 is slightly resolved from the ground. Preoutburst blue spectograms obtained by Humphreys & Aaronson reveal that Sandage 96 has a composite spectrum, dominated in the blue region by A- and B-type stars, while infrared photometry shows that Sandage 96 also contains red supergiants. These results demonstrate that Sandage 96 is a young compact cluster. We have studied the stellar population of Sandage 96, using published photometric measurements combined with a χ² fitting code. We derive a cluster age of 13.6 Myr, a reddening of 0.172, and a total stellar mass of 24,000 M☉. For this cluster age, the SN progenitor had a main-sequence mass of 15 M☉. Postoutburst photometry of Sandage 96 may establish whether the progenitor was a red or blue supergiant.

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

1. INTRODUCTION

Type II supernovae (SNe) are believed to arise from core collapses of evolved massive stars, yet there is surprisingly little direct evidence in the form of preoutburst observations of progenitor stars to support this belief. To date, the best-observed SN progenitor is the blue supergiant precursor of SN 1987A in the Large Magellanic Cloud (LMC), but the preoutburst data are limited to photographic and photoelectric photometry and a photographic objective-prism spectrum (see Wilborn et al. 1989). More recently, the progenitors of (or binary companions of) two further Type II SNe have been identified on archival images from the Hubble Space Telescope (HST) and ground-based telescopes (Maund et al. 2004; Smartt et al. 2004). See Smartt et al. (2003) for further discussion of the importance of efforts to identify SN progenitors.

The bright SN 2004dj was discovered in the nearby spiral galaxy NGC 2403 on 2004 July 31 by K. Itagaki (see Nakano 2004), and it was quickly classified spectroscopically as a normal Type II-P (plateau) core-collapse SN caught about 3 weeks after the explosion (Patat et al. 2004). NGC 2403 is a member of the M81 group, with a distance of about 3.3 Mpc (Karachentsev et al. 2004); SN 2004dj is thus the nearest SN to be discovered since SN 1993J in M81, and it is destined to be a well-observed SN II-P event. Type II-P SNe have been reviewed by Leonard et al. (2002) and Hamuy (2003); Hamuy’s Table 1, which lists the properties of 24 well-documented SN II-P events, shows that SN 2004dj is the nearest Type II-P SN yet discovered (apart from the peculiar Type II-P SN 1987A).

In this Letter, we use recent images of the SN along with archival images to show that SN 2004dj coincides with a previously cataloged object in NGC 2403, which proves to be a slightly resolved young cluster that contains dozens of massive stars. Well-calibrated photometry and digital spectrograms of this cluster exist in the literature. Using models of starburst populations, we are able to estimate the age, mass, and other properties of this compact cluster and to set limits on the nature of the progenitor star.

2. IDENTIFICATION OF THE PROGENITOR

2.1. Sandage 96 in NGC 2403

Sandage (1984) conducted a photographic survey of the brightest blue and red supergiants in NGC 2403. Based on the reported position of SN 2004dj, several authors (see Yamaoka et al. 2004) have pointed out the close coincidence of the SN with a luminous blue object in Sandage’s list, cataloged as number 96. This object is designated “Sandage 96” hereafter. Sandage 96 would be one of the brightest blue supergiants in NGC 2403, if it were a single star. However, Sandage (1984) annotated it as a possible cluster. Humphreys (1980) obtained a blue spectrum of this object and classified it as B5: I 1 but suggested a composite nature. An improved blue spectrum was obtained by Humphreys & Aaronson (1987) and is reproduced in their Figure 1. They report that the integrated spectrum resembles that of an early A-type star but that the hydrogen Balmer lines are too broad to be due solely to an A supergiant, and the presence of He I lines shows that there are also B-type stars present in the spectrum. Humphreys & Aaronson also did not detect Hα emission. They concluded that Sandage 96 is a compact cluster, without an accompanying H II region.

Sandage 96 was included as object n2403-3866 in a list of
young massive clusters in nearby galaxies by Larsen (1999), who measured Johnson-Kron-Cousins $UBV$ photometry. The object is also present in the Two Micron All Sky Survey infrared point-source catalog (Skrutskie et al. 1997), from which we obtained its $JHK_s$ photometry. The optical and infrared photometric data from these sources are given in Table 1, where we have removed the reddening correction applied by Larsen to his measurements. The data definitely do not correspond to any single star, since the color is blue at short wavelengths but an infrared excess begins to set in around the $I$ band and is pronounced in the infrared.

2.2. Archival and New Images

The site of SN 2004dj was imaged (serendipitously) by H. E. B. on three nights in 1999 January with the Mosaic CCD camera on the Mayall 4 m telescope at Kitt Peak National Observatory (KPNO). All of the observations were made with standard Johnson-Kron-Cousins $B$, $V$, and $I$ filters, along with a Thuan-Gunn $u$ filter.

Following the discovery announcement of SN 2004dj, CCD images of the SN were obtained by Y. L., D. M., E. O. O., and D. P., using the 1.0 m telescope of the Wise Observatory and $UBVRI$ filters. Figure 1 (left) shows the field of the SN and a few neighboring bright field stars, as imaged in the $V$ band with the Wise telescope on 2004 August 4. In Figure 1 (right), we show the same field, as extracted from an $I$-band KPNO Mosaic frame taken on 1999 January 19. In order to verify the association of the SN with Sandage 96, which is strongly suggested by Figure 1, we combined four of the best Wise Observatory CCD frames of SN 2004dj to produce a fairly deep image. We then registered this frame with the Kitt Peak 4 m frame shown in Figure 1, using eight nearby field stars to determine the geometric transformation of the Wise frame onto the Kitt Peak image. The rms of the astrometric fit is only 0′03 in each coordinate, in spite of the 2′6 seeing of the Wise image and the fact that several of the reference stars are saturated in the KPNO image. We find that SN 2004dj coincides with Sandage 96 to within 0′07 (0′04 in right ascension, 0′06 in declination).

Sandage 96 is slightly nonstellar on our archival frames. In our $I$ frame with the best seeing, 0′78, Sandage 96 has an FWHM of 1′0. S. Smartt (2004, private communication) has informed us that archival images taken with the 8.2 m Subaru telescope in 0′44 seeing through an Hα filter (which just measures continuum flux as there is no line emission) show an FWHM for Sandage 96 of 0′6.

TABLE 1

| Quantity | Value |
|----------|-------|
| $V$      | 18.05 ± 0.03 |
| $U - B$  | −0.48 ± 0.06 |
| $B - V$  | 0.30 ± 0.03 |
| $V - I$  | 0.87 ± 0.03 |
| $J$      | 16.193 ± 0.081 |
| $H$      | 15.539 ± 0.106 |
| $K_s$    | 15.416 ± 0.191 |

It should be noted that, at the distance of NGC 2403, 1″ corresponds to a linear scale of 16 pc and that 4 pc is a typical size for a compact young stellar cluster (see, e.g., Maíz-Apellániz 2001). There is thus no doubt that the SN lies well within the bounds of the cluster Sandage 96 and that it must have arisen from a star belonging to the cluster.\(^5\)

3. THE STELLAR POPULATION OF SANDAGE 96

3.1. Mathematical Approach

In order to determine the nature of the stellar population within the compact cluster and thus constrain the main-sequence mass and other properties of the SN 2004dj progenitor, we used CHORIZOS (Maíz-Apellániz 2004), a $\chi^2$ minimization code that finds which members of a family of spectral energy distributions (SEDs) are compatible with the observed integrated colors of a stellar population. CHORIZOS allows the user to select different input SED families and extinction laws and to place statistical constraints on the fitted parameters.

Although the above discussion shows that Sandage 96 is a cluster, for completeness we tested whether this object could have been a single luminous supergiant or had to be a compact cluster, by using two different SED families, one consisting of single stars and the other of cluster populations. For the stellar models, we selected R. L. Kurucz\(^6\) atmospheres with low grav- ities, solar metallicity, and effective temperatures between 3500 and 50,000 K. For the cluster models, we selected Starburst99 (Leitherer et al. 1999) model populations with solar metallicity, a Salpeter initial mass function (IMF), an upper mass cutoff of 100 $M_{\odot}$, and ages between 10$^6$ and 10$^{10}$ yr. The starburst models assume that all of the stars in the population were created at the same time. The choice of solar metallicities for the models is justified by the Galactocentric distance of Sandage 96 (Fierro et al. 1986).

CHORIZOS was executed using both SED families, selecting a Cardelli et al. (1989) interstellar extinction law with $R_{V,s} = 3.1$ and two free parameters: the extinction, $E(B-V) = 5.495$, and either the effective temperature (for the stellar models) or

\(^5\) After this Letter was submitted, $HST$ observations of SN 2004dj were obtained on 2004 August 16 and 17. Based on long-exposure ACS/WFC images, Filippenko et al. (2004) report (and we confirm independently) that, although the SN is heavily saturated in these frames, it definitely took place at a position coincident with Sandage 96. We have analyzed higher resolution ACS/HRC images that were also obtained and find that (1) in the short-exposure (nonsaturated) images, only a very bright point source (the SN itself) is present, which is so bright that it makes detection of any other stars in the cluster extremely difficult; and (2) in the NUV-objective-prism exposures, the SN is easily detected as well as three nearby (within a few arcseconds) stars also detected in the ground-based KPNO image. All of the $HST$ images confirm the coincidence between SN 2004dj and Sandage 96, but it will take additional observations, after the SN has subsided, to determine the color-magnitude diagram and other properties of the cluster.

\(^6\) See http://kurucz.harvard.edu.
log (age) (for the cluster models). Since we are fitting two parameters and using six colors (derived from seven magnitudes), the problem has 4 degrees of freedom.

3.2. Results of the Population Fitting

Our results from CHORIZOS decisively eliminate the possibility that Sandage 96 is a single luminous star. The best fit for the Kurucz models is for a highly reddened O star, but its reduced $\chi^2$ is 43, indicating the extremely poor quality of the fit.

However, cluster models provide an excellent fit, with a best reduced $\chi^2$ of 0.28 (which, if anything, suggests that photometric uncertainties may have been overestimated). The likelihood map produced by CHORIZOS (Fig. 2) shows two peaks in the log (age)-$E(4405 - 5495)$ plane, indicating the existence of two solutions compatible with the available photometry. Properties for both solutions are shown in Table 2. The “young” solution (age of 13.6 Myr) is the one that has the highest likelihood. The “old” solution (age around 29 Myr) is less likely, but its validity cannot be immediately rejected at the 10% level, since its reduced $\chi^2$ is 1.74. The SED for the young solution is shown in Figure 3.

Figure 2 shows that the fit to the young solution is excellent. For the old solution, the largest contribution to $\chi^2$ is from the $U$ band, because the Balmer jump of the SED is large compared to the observed photometry (and to the spectrum shown by Humphreys & Aaronson 1987). Therefore, we strongly prefer the young solution.

This solution yields a reddening of $E(4405 - 5495) = 0.172 \pm 0.022$, which is in very good agreement with the $E(B - V) = 0.18$ obtained by Patat et al. (2004) from the Na D equivalent width in the SN spectrum.

The age of 13.6 Myr derived above is also compatible with other secondary evidence. The blue spectrum of a 13.6 Myr old cluster is dominated by blue giants and supergiants, so its classification as composite B5: I by Humphreys (1980) agrees with our expectation. Furthermore, NGC 2403 is a galaxy that has undergone recent intense episodes of star formation that have produced several massive young clusters and OB associations (Drissen et al. 1999; Maíz-Apellániz 2001). Some of those clusters are only a few megayears old and show strong H$\alpha$ emission; however, as noted above, Sandage 96 is not detected in H$\alpha$ (see also Sivan et al. 1990). This is what is expected for a 13.6 Myr old cluster, since such an object would have had enough time to disperse its parent molecular cloud by stellar winds and SN explosions and should have no O stars left (apart from, possibly, O stars formed as a result of mass transfer in binaries; Cerviño 1998).

4. DISCUSSION

The turnoff mass for a cluster at an age of 13.6 Myr is 15 $M_{\odot}$, and the corresponding main-sequence spectral type is B1 V.

![Fig. 2.—Likelihood contour plot in reddening vs. age for the CHORIZOS fit using Starburst99 models. Age is expressed in years. The favored solution has a cluster age of 13.6 Myr and a reddening of 0.172 mag.](image1)

![Fig. 3.—SED for the best fit (13.6 Myr solution) to the optical-NIR photometry of Sandage 96, based on Starburst99 models of integrated stellar populations. The photometry itself is shown by the symbols with error bars (vertical ones for uncertainties and horizontal ones for the approximate wavelength coverage of each filter). Star symbols indicate the calculated magnitude of the model SED for each filter.](image2)
From the known distance and measured $V$ magnitude, we can determine the total mass of the stellar population. The result, $\approx 24,000 M_\odot$, makes Sandage 96 intermediate between the most massive young clusters in NGC 2403 and typical Galactic open clusters, with a mass similar to those of some of the “rich” young clusters in the LMC. Therefore, Sandage 96 is likely not massive enough to survive for a Hubble time and become a future globular cluster; rather, it is destined to dissolve into the general field of NGC 2403 (Fall & Zhang 2001).

The uncertainties quoted in Table 2 should be taken with caution, since they do not include external error sources, such as uncertainties in the distance, stellar models, and other assumptions, including the assumed instantaneous starburst episode. In particular, we should note that current stellar evolutionary models have problems in producing the right numbers and types of red supergiants in the 6–30 Myr age interval (Langer & Maeder 1995; Massey & Olsen 2003). Therefore, it is possible that the actual age for Sandage 96 may differ from our value by 1 or 2 Myr. Unless the cluster is very compact, future $HST$ imaging should provide a color-magnitude diagram that will clarify these issues.

Another point is that our starburst models assume an infinite number of stars, whereas the actual number of bright stars in Sandage 96 must be relatively low, leading to a potential problem of stochastic sampling. However, as we show in Table 2, the predicted numbers of red supergiants in Sandage 96 (the main contributors to the NIR SED) and of blue giants and supergiants (the main contributors to the blue-visible spectrum) are above the critical value of 10 (Cerviño & Valls-Gabaud 2003), below which sampling effects start to become significant.

Type II-P SNe are expected to have red supergiant progenitors with initial masses lower than those of Type II-L and Ib/c (Heger et al. 2003). The cutoff mass we find for Sandage 96, $15 M_\odot$, is consistent with that of other Type II-P SNe (Smartt et al. 2003). However, it should be pointed out that the heretofore best-studied SN progenitor of a core-collapse SN, that of SN 1987A, turned out to be a blue supergiant. As seen in Table 2, our models predict that $\approx 12$ red and two to three blue supergiants should have been present in Sandage 96 prior to the explosion of SN 2004dj. Given that red supergiants are the dominant sources of the NIR flux in a 13.6 Myr old cluster, and that blue giants and supergiants dominate in the $U$ and $B$ bands, we can make a prediction that will test the nature of the progenitor. Once the SN has faded away, if the star that exploded was a red supergiant, then the NIR integrated magnitudes of the cluster should have dimmed by about 0.08 mag, while the blue magnitudes will be essentially unchanged. If, on the other hand, the progenitor was a blue supergiant, the $UBV$ photometry should be dimmer by $\approx 0.04$ mag. However, it will take several years before the SN has faded enough to make a negligible contribution to the total flux of Sandage 96 (Pozzo et al. 2004; Zhang et al. 2004).

We conclude that SN 2004dj took place in Sandage 96, an $\approx 14$ Myr old compact cluster of intermediate mass. Based on its SN type of II-P and the $15 M_\odot$ cutoff mass of the cluster, the progenitor is likely to have been a red supergiant, of which $12 \pm 4$ existed in Sandage 96 prior to the explosion. Although a blue supergiant progenitor cannot be ruled out completely at this stage, our population models suggest that a comparison of pre- and postoutburst photometry of Sandage 96 may determine whether the exploded progenitor was blue or red.

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ERRATUM: “THE PROGENITOR OF THE TYPE II-P SN 2004dj IN NGC 2403” (ApJ, 615, L113 [2004])

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This figure replaces Figure 2 in the original Letter. The figure was generated automatically several times by a computer code, and during the revision process, an incorrect version was submitted. In the published version, only a single solution (the young one) was apparent in the likelihood contour plot, but the existence of a second, older one was discussed in the text. The second peak had disappeared because of an incorrect choice of contour levels. The same data are plotted here with a lower minimum contour, thus revealing the existence of the older solution.

![Figure 2](image)

**Fig. 2.**—Likelihood contour plot in reddening vs. age for the CHORIZOS fit using Starburst99 models. Age is expressed in years. The favored solution has a cluster age of 13.6 Myr and a reddening of 0.172 mag.