THE TYPE IIN SUPERNOVA 2002KG: THE OUTBURST OF A LUMINOUS BLUE VARIABLE STAR IN NGC 2403

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ABSTRACT

We show that Supernova (SN) 2002kg in NGC 2403, initially classified as Type II-narrow (IIn), has photometric and spectroscopic properties unlike those of normal SNe. Its behavior, instead, is more typical of highly massive stars which experience the short-lived luminous blue variable (LBV) phase toward the end of their lives. The star, in fact, most resembles the LBV S Doradus in outburst. The precursor of SN 2002kg is the irregular, bright blue variable star 37 (V37), catalogued by Tamann & Sandage in 1968. Using high-quality ground-based, multi-band images we can constrain the initial mass of V37 to be $M_{\text{ini}} \gtrsim 40 M_{\odot}$. We find that, although the spectra indicate a nitrogen enhancement, possibly revealing the products of CNO processing by V37 in the ejecta, the star lacks a substantial LBV nebula. The outburst from SN 2002kg/V37 is not nearly as energetic as the giant eruptions of the $\eta$ Carinae-like variables, such as SN 1954J/V12, also in NGC 2403. SN 2002kg/V37, however, is among a growing number of "SN impostors" exhibiting a broad range of outburst energetics during a pre-SN phase of massive-star evolution.

Subject headings: supernovae: general — supernovae: individual (SN 2002kg) — stars: early-type — stars: evolution — stars: variables: other — Hertzsprung-Russell (HR) diagram — galaxies: individual (NGC 2403)

1. INTRODUCTION

The evolution of the most massive stars is not well understood. After the main sequence, stars with masses $M \gtrsim 20–30 M_{\odot}$ should go through the red supergiant phase, or directly to a short-lived luminous blue variable (LBV) phase, to become Wolf-Rayet stars (e.g., Langer et al. 1994; Stothers & Chin 1996) before termination as supernovae (SNe; e.g., Woosley, Langer, & Weaver 1993) or “collapsars” (e.g., MacFadyen & Woosley 1999). LBVs which experience normal eruptions or outbursts generally increase in brightness by one or two visual magnitudes, but remain relatively constant in bolometric luminosity (Humphreys & Davidson 1994). However, the extremely rare case of $\eta$ Carinae (e.g., Davi-
son & Humphreys 1997) shows that some very massive stars go through tremendous eruptive phases of mass ejection prior to the end of their lives. An estimate of the initial mass for \( \eta \) Car is \( \gtrsim 150 M_\odot \) (Hillier et al. 2001). The very massive stars define the upper luminosity boundary of the Hertzsprung-Russell (HR) diagram. It would, of course, be very instructive to determine the prevalence of (and mass range for) the stars which undergo outbursts prior to becoming a SN.

Several recent luminous events which have been identified as SNe are probably not genuine SNe at all. Instead, it is argued that these are more likely to be super-outbursts of very massive stars, analogous to \( \eta \) Car (Goodrich et al. 1989; Filippenko et al. 1995; Van Dyk et al. 2000). The energetics are comparable to those of SNe; hence, these objects act as SN “impostors.” The “classical” examples are SN 1954J/V12 in NGC 2403 (Humphreys, Davidson, & Smith 1999; Smith, Humphreys, & Gehrz 1999; Van Dyk et al. 2005) and SN 1961V in NGC 1058 (e.g., Van Dyk, Filippenko, & Li 2002, Van Dyk 2005; however, see Chu et al. 2004). Two more well-studied cases are SN 1997bs in M66 (Van Dyk et al. 2000) and SN 2000ch in NGC 3432 (Wagner et al. 2004). These objects were all underluminous and exhibited photometric behavior unlike that of any normal SNe. For SN 1997bs, Van Dyk et al. (1999) identified a luminous precursor star, with \( M_V \sim -8.1 \) mag, in an archival Hubble Space Telescope (HST) WFPC2 F606W image. Unfortunately, no color information was available for the star to compare it to theoretical evolutionary models, in order to derive or strictly constrain the star’s mass.

In this paper we present another similar case, SN 2002kg, also in NGC 2403, which we similarly argue is not actually an explosion at the end of a massive star’s life, but instead is the powerful eruption of a LBV. SN 2002kg was discovered on 2003 October 22 (UT dates are used throughout this paper) by Schwartz & Li (2003) with the Tenegra II and Katzman Automatic Imaging Telescope (KAIT; Li et al. 2000; Filippenko et al. 2001; Filippenko 2005); it first became visible in images taken on 2002 October 26 (UT dates are used throughout this paper).

In Figure 1 we show a KAIT image of the SN in the host galaxy. Filippenko & Chornock (2003) identified the SN spectroscopically as a Type II-“narrow” supernova (SN IIn; Schlegel 1990, Filippenko 1991, 1997); it has Balmer emission lines exhibiting a narrow component atop a broader base, but with characteristics more similar to those of SN 1997bs (Van Dyk et al. 2000) than to the prototypical SNe IIn (e.g., SN 1988Z, Turatto et al. 1993; SN 1995N, Fransson et al. 2002).

In Van Dyk (2005) we first identified SN 2002kg with a previously known luminous irregular blue variable (V37) in the host galaxy and provided an estimate of the initial mass of this precursor star. Here we present a more detailed discussion. Weis & Bomans (2005) also have recently identified SN 2002kg with V37 and discuss its historical light curve.

2. OBSERVATIONS

2.1. Photometry of the Outburst

2.1.1. KAIT Monitoring

Since the host galaxy has been monitored frequently by KAIT we are able to obtain unfiltered \((\sim R)\) photometry for the SN 2002kg outburst over a period of more than one year. Li et al. (2003) discuss how the unfiltered magnitudes for an object can be transformed to standard \(R\) magnitudes, with knowledge of its detailed color evolution. If the object’s color remains unchanged, then the transformation is merely a constant offset. We find that the SN has approximately the same color (within \(\sim 0.1\) mag) at both an early and late time in the outburst (see §5); we could therefore follow the prescription in Li et al. (2003) to derive the offset.

Equivalently, we can simply adjust the KAIT magnitudes, by about \(-0.7\) mag, based on the offset between the unfiltered magnitude from the March 25.17 (JD 2452723.67) KAIT observation and the \(R\)-band magnitude from the March 26.15 (JD 2452724.65) Palomar observation (see §2.1.2; we consider the likely change in the \(R\) magnitude over about one day to be insignificant for our purposes). We note that systematic errors in the magnitudes probably still exist for this KAIT light curve, due to the broad spectral range of the unfiltered images and the assumption of constant color for SN 2002kg (which may not apply for the entire outburst). We list the resulting \(R\) magnitudes in Table 1 and show the light curve in Figure 2, after further correcting for both extinction (see §3) and the true distance modulus to NGC 2403 \((\mu_0 = 27.48\) mag; Freedman et al. 2001).

The light curve shows highly erratic and un-
usual behavior for a SN. The maximum $R$ luminosity is about $-10.2$ mag, more than 7 mag fainter than a typical SN IIn (see Van Dyk et al. 2000, their Figure 5). In fact, this light curve is more qualitatively similar to those of the possible $\eta$ Car analog, SN 2000ch (Wagner et al. 2004, their Figure 3), or the LBV S Doradus (Humphreys & Davidson 1994; their Figure 2). Schwartz & Li (2003) note that SN 2002kg is not detectable, $R \gtrsim 19.5$ mag ($M_R \gtrsim -8.0$ mag), in a KAIT image from 1998 November 13. Apparently we first caught the SN with KAIT while it was already undergoing the observed outburst (this is supported by the lack of detection at earlier epochs, based on data from other telescopes; see §2.1.2). The absolute magnitude of this outburst was already $\gtrsim 2$ mag brighter at that time than when the precursor star was in quiescence (see also §3).

As Schwartz & Li (2003) point out, the light curve shows a brightening trend between 2002 October 26, when the outburst was first noticed, and 2003 early January. The light curve then shows a noticeable dip after 2003 January 1, before reaching maximum near 2003 mid-March. The brightness declines yet again by late March. No coverage exists from KAIT between 2003 late March and mid-October, so we have no knowledge of the outburst behavior during that interval. However, by October 11 SN 2002kg has approximately the same brightness as it did in late March. During 2003 October and November the object remains at a relatively constant brightness. We then see a pronounced dip in the light curve, after 2003 late November through 2004 early March. The light curve rises again into 2004 early April, at which time our KAIT coverage terminates. This is similar to the behavior of SN 2000ch; Wagner et al. (2004) speculate that the dip seen for SN 2000ch may be due to either a dust formation event, an eclipse, or changes within an optically thick ejected envelope. For SN 2002kg, this dip is much broader in time than was seen for SN 2000ch. We suspect that for SN 2002kg the light curve dip is more likely due to opacity changes in the ejected envelope than to dust formation (see §4).

2.1.2. Other Ground-Based Imaging

As already mentioned, we obtained $R$, as well as $BVI$, images of SN 2002kg with the Palomar 1.5-m telescope on 2003 March 26.15. In Figure 3 we show the $V$-band image. We extracted instrumental magnitudes for the relatively bright SN 2002kg in the Palomar images via fitting an empirically derived model point-spread function (PSF) for each band, using DAOPHOT (Stetson 1987) within IRAF$^2$. Unfortunately, no photometric calibration was obtained during these Palomar observations. However, Larsen & Richtler (1999) also obtained $UBVRI$ (plus H$\alpha$) images of NGC 2403 with the Nordic Optical Telescope (NOT)$^3$ on 1997 October 13, prior to SN 2002kg, under very good seeing conditions of $0.8''$. (We will discuss these NOT images in more detail in §3.)

We extracted instrumental magnitudes from the NOT broad-band images using IRAF, first with a $4''$ aperture and then with a PSF for each band. Calibration was established using photometry of a number of isolated stars through a $20''$ aperture, which matches the aperture used to establish the calibration through standard-star observations by Larsen (1999; we also applied the appropriate extinction corrections, supplied via a private communication from S. S. Larsen). We have compared our photometry with the $BV$ bright-star photometry of Sandage (1984) and $UBV$ photometry of Zickgraf & Humphreys (1991) and find good agreement across all bands.

We tie the photometry from the Palomar images to that from the calibrated NOT images and list the results in Table 2. As mentioned above in §2.1.1, we used the $R$ magnitude for SN 2002kg from these Palomar data to adjust the unfiltered KAIT light curve. We also include this $R$ magnitude from Palomar in the light curve shown in Figure 2.

A number of images of NGC 2403 obtained in several bands prior to 2002 October are also available in the Isaac Newton Group archive. These images have a range of sensitivities, and SN 2002kg is not detected in any of them. We list the resulting upper limits to detection of the outburst in Table 2.

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$^2$IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

$^3$The NOT images were contributed to the NASA/IPAC Extragalactic Database (NED) and posted for public distribution on their website, http://nedwww.ipac.caltech.edu.
2.1.3. HST Imaging

Additionally, SN 2002kg was observed on 2004 August 17 with the Wide Field Channel (WFC) and on 2004 September 21 with the High Resolution Channel (HRC) of the Advanced Camera for Surveys (ACS), on-board HST. The August observations were obtained during a campaign by program GO-10182 (PI: Filippenko) to observe SN 2004dj, the third historical SN in NGC 2403. The imaging strategy for SN 2004dj was purposely designed so that the site of SN 2002kg would also be contained in the WFC images. The September observations were obtained as part of a larger Snapshot program observing SNe (GO-10272; PI: Filippenko). The WFC exposures were 600 s in F475W, 650 s in F658N, and 350 s each in F606W and F814W. The HRC exposures were 840 s in F435W and 360 s in F625W. The images were all extracted from the HST archive. For the WFC data we recomposed the individual “flt” exposures in all four bands at the Space Telescope Science Institute (STScI), in order to more reliably remove cosmic-ray hit features from the images, and, in effect, produce our own drizzled (Fruchter & Hook 2002) “drz” images independent of the HST data pipeline.

The WFC F606W image is shown in Figure 4. We performed PSF-fitting photometry within IRAF/DAOPHOT on the broad-band WFC images. The empirical PSF for each band was derived from the ∼10 brightest, uncrowded, and unsaturated stars in these images, based on a 0′′5 aperture. For the WFC narrow-band image, we performed aperture photometry only, using a 0′′5 aperture. We determined that any correction to the magnitudes for the degradation of charge-transfer efficiency (CTE) is <0.2% in all bands (see Riess & Mack 2004). Next, for the F475W and F606W filters we applied the corrections from Table 5 in Sirianni et al. (2005); for the F814W filter, we applied the correction from their Table 6, assuming the effective wavelength from their Table 8 for approximate spectral type F2. We then applied the zero points (VEGAMAG for the broad bands, and STMAG for the narrow band) in Table 10 of Sirianni et al. to the corrected instrumental magnitudes. The resulting flight system magnitudes are \( m_{F475W} = 19.43 \pm 0.02 \), \( m_{F606W} = 19.26 \pm 0.02 \), \( m_{F814W} = 19.13 \pm 0.03 \), and \( m_{F658N} = 18.67 \pm 0.14 \).

In the HRC images SN 2002kg is relatively isolated, so we simply employed aperture photometry (assuming a 0′′5 radius aperture) within IRAF. We then applied the corrections to infinite aperture from Table 5 and the zero points from Table 11 in Sirianni et al. (2005). The resulting flight system magnitudes are \( m_{F435W} = 19.41 \pm 0.05 \) and \( m_{F625W} = 19.16 \pm 0.04 \).

Finally, we transformed the broad-band magnitudes into the Johnson-Cousins system, also following Sirianni et al., keeping in mind the fact that SN 2002kg shows strong emission lines (Filippenko & Chornock 2003, and also §2.2), whereas the stars used to establish the transformations all show normal absorption-line spectra. We list the resulting magnitudes in the standard photometric system in Table 2. We also include the HRC \( R \)-band data in the light curve shown in Figure 2.

2.2. Spectroscopy of the Outburst

Optical spectra of SN 2002kg were obtained at the Keck 10-m telescope with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on 2003 January 6 (the confirmation spectrum; JD 2452646.0) during the early brightening trend, on 2003 November 29 (JD 2452973.0), prior to the pronounced dip in brightness, and on 2004 December 12 (JD 2453352.03) at relatively later times. These observations had spectral resolution of ∼6 Å across most of the spectral range, 3000–9430 Å (the resolution is somewhat worse in the near-infrared). The 2004 December spectrum was obtained with a 600-line grism on the blue side, whereas the other two LRIS spectra were obtained with a 400-line grism in the blue. At Hα the resolution (FWHM) of these spectra is ∼320 km s\(^{-1}\).

In addition, a spectrum was obtained on 2003 November 20 (2452964.0), while the object was still bright, with the blue channel of the spectrograph on the 6.5-m Multiple-Mirror Telescope (MMT). A 300-line grating was used, with spectral range 3700–8300 Å. For the Keck spectra conventional data reductions were performed within IRAF, including bias subtraction, flat-fielding, and wavelength calibration, while our own IDL\(^4\) routines were used for flux calibration and removal of telluric lines (e.g., Matheson et al. 2000). Reduction of the MMT spectrum was performed in a similar fashion.

The spectra are shown in Figure 5. The overall shape of the continuum has remained rela-

\(^4\)IDL is the Interactive Data Language, a product of Research Systems, Inc.
tively blue throughout 2003 and 2004, peaking near 3700 Å. The spectra all show several strong emission lines, primarily of H, but also of possible weak Fe II at 4500–4600 Å and at 5150–5350 Å, as well as possible blends of H with He I. Figure 6 shows just the Hα plus [N II] λλ6548, 6584 Å lines. The narrow Balmer profiles are unresolved, and the broad profiles at Hα remain relatively constant throughout 2003 and 2004, with Gaussian velocity widths $\sigma \approx 370$ km s$^{-1}$. Such a velocity width for the line is uncharacteristically low for a young SN, but consistent with the terminal wind velocities for LBVs. The presence of the prominent, unresolved [N II] emission lines, while other forbidden lines (e.g., due to O and S) appear weak or absent, suggests a possible N enhancement in the circumstellar gas.

From the line profiles in Figure 6 it is clear that the power in the Hα+[N II] emission has steadily declined. This trend is consistent with that of the R-band light curve for the observation dates of the spectra. In fact, integrating over the continuum-subtracted Hα+[N II] line profiles shown in Figure 6, we find an observed flux $F_{\text{H}\alpha+[\text{NII}]} \approx 1.3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (uncorrected for extinction) in 2003 January, $\sim 1.1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in 2003 November, and $\sim 4.5 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ in 2004 December. (The absolute flux scale for the Keck spectra is accurate to $\sim 20\%$ or better.)

In the blue portion of the spectra, shown in Figure 7, we see most notably the presence of various absorption lines, mostly due to higher-order Balmer lines, and possible blends with He I. Strong Ca II H and K lines (the H component is also probably blended with He) are also seen, particularly in 2003, but we suspect these lines are dominated by interstellar absorption local to the SN (the extinction toward the SN appears to be significant; see §3).

Such absorption features are not typically seen in SN spectra. (We have been very careful in the extraction of the spectra from the 2-dimensional images and can safely rule out contamination by a neighboring star.) The equivalent widths of these lines indicate an underlying star with spectral type and luminosity class of a late O or early-to-mid B supergiant. We compare the SN 2002kg spectra to those of the LBV S Dor (from 1996, during outburst; Massey 2000) and the well-studied S Dor-type LBV AG Carinae (in a deep minimum state; Walborn & Fitzpatrick 2000). Although the Balmer emission lines for SN 2002kg lack the P-Cygni profiles seen in the AG Car spectrum, the SN spectra, overall, show a remarkable resemblance to that of S Dor in outburst. We therefore consider the spectroscopic evidence quite compelling that SN 2002kg is not a true SN, but instead a S Dor-like LBV in outburst. A similar conclusion was also reached by Weis & Bomans (2005).

3. VARIABLE 37: THE VERY MASSIVE PRECURSOR OF SN 2002KG

From the Palomar images (§2.1.2) we measure an accurate absolute position for the SN of $\alpha(J2000) = 7^h 37^m 01^s.66, \delta(J2000) = 65^\circ 34' 28.0'',$ with a total uncertainty of $\pm0''.2$, using the Two Micron All Sky Survey (2MASS) as the astrometric reference (see Van Dyk, Li, & Filippenko 2003). This position differs by $1''.7$ from that reported by Schwartz & Li (2003), and results in an offset from the host galaxy’s nucleus of 63''6 east and 101''2 south. We then applied the same astrometric grid to the NOT images (with a $\pm0''.2$ total uncertainty in the grid). In Figure 8 we show the NOT V-band image from 1997. When the absolute SN position is superimposed on this image, it coincides exactly with the star indicated by the arrow in the figure. This star is almost certainly the precursor of SN 2002kg.

We find that this star had $V = 20.63 \pm 0.04, U - B = -0.96 \pm 0.05, B - V = -0.08 \pm 0.05, V - R = 0.09 \pm 0.04,$ and $V - I = -0.06 \pm 0.05$ mag (see Table 2). (Uncertainties include the uncertainties in the standard calibration in each band from Larsen 1999, his Table 1, added in quadrature with the measurement uncertainties from IRAF.) The fainter ($V = 21.01 \pm 0.04$ mag), redder ($V - I = 0.50 \pm 0.05$ mag) star $\sim 1''0$ to the northeast is well outside the total uncertainty in the SN position in the NOT image, $0''.3$ (summing in quadrature the total uncertainty in the SN position measured from the Lick image and the uncertainty in the astrometric grid on the NOT image). Also, this fainter star appears at approximately this same brightness (to within one magnitude) and color in the HST images as in the NOT images, whereas SN 2002kg (and therefore its precursor) have changed more significantly both in brightness and in color (compare Figure 8 with Figure 3 and see Table 2). We note that Weis & Bomans (2004) also attempt to identify the precursor, but, using pre-outburst ground-based images with inferior spatial resolution, they are
unable to distinguish the star we have identified as the precursor from its fainter neighbor without consulting the post-outburst HST images.

This precursor star had actually been identified first by Tammann & Sandage (1968) in their photographic study of supergiants in NGC 2403. We have determined this from a careful astrometric comparison of their Figure 5, an enlargement of a 103aO photographic plate of the galaxy, with the NOT V-band image. The SN precursor star we have identified lines up very well with the position of the catalogued bright blue irregular variable star, no. 37 (hereafter, V37) from Tammann & Sandage (1968). We consider the positional coincidence a compelling indication that the two stars are one and the same (see also Weis & Bomans 2005).

Tammann & Sandage (1968) describe the B light curve for V37 as exhibiting relatively small amplitudes of $\sim 2$ mag, between about 19 and 21 mag, and characteristic fluctuation timescales of several years (see their Figure 10). Where data were available between about 1948 and 1963, the observed $B - V$ color of V37 apparently fluctuated between +0.20 and −0.36 mag. The maximum absolute $B$ magnitude for V37 during their monitoring was $\sim −8.8$, although generally it was $\sim −6.5$ mag.

We can estimate the extinction and reddening to this star by placing it in color-color diagrams (Figure 9), based on the NOT and HST ACS/WFC photometry. Also shown in both diagrams are the loci of the main sequence and supergiants (Drilling & Landolt 2000), and the reddening vector for OB supergiants, assuming a Cardelli, Clayton, & Mathis (1989) reddening law. Figure 9a, in particular, implies that the star is a blue supergiant reddened along this vector, at $A_V = 0.6 ± 0.2$ mag ($E[B−V] = 0.19 ± 0.06$ mag). Most of this extinction must be in the star’s local environment; the component of the Galactic foreground extinction alone is only $A_V = 0.13$ mag (Schlegel, Finkbeiner, & Davis 1998). In Figure 9 we also show the loci of stars in the precursor’s immediate ($\sim 200$ pc) environment; the reddening in the environment appears to be quite variable, with many stars more reddened than the precursor. (The fainter star $\sim 1''$ to the northeast is quite reddened, with $A_V \approx 2$ mag.) The extinction toward the precursor is generally consistent with the interstellar extinction for stars in its environment.

Correcting the star’s observed photometry for the implied extinction and reddening, as well as for the true distance modulus of NGC 2403 ($\mu_0 = 27.48 ± 0.1$ mag; Freedman et al. 2001), we find $M_V^0 = −7.45 ± 0.23$, $(U−B)_0 = −1.02 ± 0.07$, $(B−V)_0 = −0.13 ± 0.08$, $(V−R)_0 = −0.01 ± 0.05$, and $(V−I)_0 = −0.30 ± 0.09$ mag. (The total uncertainty in the absolute magnitude is the measurement uncertainty and the uncertainty in the distance modulus, added in quadrature; the total uncertainties in the colors include the measurement uncertainties and the uncertainty in the reddening, assuming the Cardelli et al. 1989 reddening law, again added in quadrature.) The precursor indeed appears to be a very luminous, blue supergiant of type O9 to B2. This identification of the star’s type, based on color alone, is consistent with that inferred from the underlying absorption-line features in the SN spectra.

During outburst, as seen in Figure 9b from the 2003 March Palomar data, the star has developed the observed colors of a late A-type or early F-type supergiant. V37, therefore, is following the typical behavior of a normal LBV during outburst: a “pseudo-photosphere” expands in an optically thick stellar wind, increasing the star’s V brightness by $sim 2–3$ mag (from $V = 20.63$ to $V \approx 18$), while decreasing the apparent stellar temperature to $T_{eff} \approx 8000$ K (although the concept of $T_{eff}$, as applied to LBVs in eruption, loses its true meaning, and really something more like an “apparent temperature” $T_{app}$ is appropriate; see Humphreys & Davidson 1994), without a substantial increase in reddening due to dust formation or change in the bolometric magnitude, $M_{bol}$ (Humphreys & Davidson 1994). The formation of extended, dense, dusty ejecta, such as in the super-outbursts of $\eta$ Car (Humphreys & Davidson 1994; Davidson & Humphreys 1997) and SN 1954J/V12 (Van Dyk et al. 2005), appears to be relatively exceptional behavior.

At $T_{eff} = 7000–9000$ K, the bolometric correction is zero or nearly zero (at most, about $−0.2$ mag). Therefore, for V37 at maximum light during the outburst, $M_{bol} \approx M_V \approx −9.8$ mag (assuming $A_V = 0.6$ mag and that the 2003 March Palomar V measurement is near maximum, to within $\sim 0.2$ mag). If we assume that $M_{bol}$ has remained constant, pre-outburst and at maximum, then, with the intrinsic pre-outburst color of the star, $(B−V)_0 = −0.13$ mag, and the corresponding $T_{eff} \approx 15500$ K, we can place the star in a
HR diagram and estimate the initial mass of the precursor.

We show the star’s location in such a HR diagram in Figure 10. For comparison we show the theoretical evolutionary tracks from Lejeune & Schaerer (2001), with enhanced mass loss for the most massive stars, for a 120, 85, 60, and 40 $M_\odot$ star. In Figure 10a we show the tracks assuming solar metallicity ($Z = 0.02$). It is also possible, however, that the star may have had abundances different from solar. SN 2002kg is 119.5 from the galaxy nucleus, which translates to a galactocentric distance $R \approx 1.9$ kpc. From a study of the metallicity gradient in NGC 2403 by Garnett et al. (1997), the value of log(O/H)+12 at this distance is 8.6 dex. With the solar log(O/H)+12 abundance at 8.8 dex (Grevesse & Sauval 1998), the metallicity in this region of the galaxy may actually be somewhat subsolar; thus, in Figure 10b we show the tracks calculated at the next lowest metallicity, $Z = 0.008$, as well.

What can immediately be seen from this figure, regardless of metallicity, is that the SN 2002kg precursor, V37, is well off the zero-age main sequence and is in a more evolved evolutionary phase. We conclude that the initial mass for V37 is $M_{\text{ZAMS}} \geq 40 M_\odot$. Unfortunately, we cannot be more restrictive in our initial mass estimate, since, due to the uncertainties in the photometry, distance, and reddening of the star, the termini of the 120, 85, and 60 $M_\odot$ tracks are also consistent with this photometry. Nonetheless, the HR diagrams indicate that V37 is indeed a very massive star in the upper regions of the HR diagram, consistent with the theoretical mass estimates of stars which go through the LBV phase.

4. A LBV NEBULA AROUND SN 2002KG/V37?

From the NOT and ACS/WFC Hα images, we can investigate the gaseous environment of V37, both before and during outburst. Weis & Bomans (2005) have pointed out that in both the HST images obtained in the F658N band and ground-based images from 2001, net Hα emission is seen at the position of the star. However, Humphreys & Aaronson (1987) describe a spectrum of the star obtained in 1985 as consisting of absorption lines and a blue continuum (consistent with features seen in our own spectra of SN 2002kg/V37), but with no emission lines visible. Weis & Bomans speculate that the observed Hα emission is due to the formation of a LBV nebula, associated with the current outburst or possibly ejected during an earlier evolutionary phase (e.g., Lamers et al. 2001).

We confirm that net Hα (+ [N II]) emission is associated with the star at least as early as 1997, by subtracting the NOT R continuum image from the Hα narrow-band image, after first intensity-scaling the two images (this technique can do a reasonable job of removing the continuum, when a specific narrow-line bandpass filter contiguous to Hα in wavelength is not available; see Waller 1990). We show the result of this subtraction in Figure 11; there is a very compact (i.e., unresolved and not extended) Hα (+ [N II]) source at the exact position of the star.

We would expect a star with spectral type O9–B2 to have an associated photoionization (H II) region. If we scale the NOT net Hα (+ [N II]) image by fluxes for the giant H II regions S158, S256, and S298 in NGC 2403 (Sivan et al. 1990; Drissen et al. 1999), we find a flux $F_{\text{Hα+[NII]}} \approx 1.1 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ for the nebula (uncorrected for extinction). We can correct for extinction using the relation $A_{\text{Hα}} = 0.81A_V$ from Viallefond & Goss (1986), and with $A_V = 0.6$ mag (assuming the line-of-sight extinction to the H II region is the same as that toward the precursor), we find $1.7 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. At the distance of NGC 2403 (Freedman et al. 2001) this results in a luminosity $L_{\text{Hα+[NII]}} = 2.1 \times 10^{36}$ erg s$^{-1}$. Using the relation $N_{\text{LyC}} = 7.25 \times 10^{11}L_{\text{Hα}}$ to derive the number of ionizing Lyman continuum photons ($1.5 \times 10^{48}$), and using Table II of Panagia (1973), we find that this is the approximate equivalent of the ionizing flux from a single B0 I star. That is, the Hα emission seen in 1997 is at least consistent with a H II region produced by the ionizing flux of a single massive blue supergiant — the outburst precursor, V37.

Subtracting the continuum in the F606W band from the 2004 August ACS/WFC F658N image, and scaling the net emission image to the fluxes of the giant H II regions S256 and S298, results in a flux $F_{\text{Hα+[NII]}} \approx 5.2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (uncorrected for extinction) for SN 2002kg. This is approximately a five-fold increase in the Hα flux during outburst in late 2004, relative to the pre-outburst state. We have already seen from §2.2 that in 2003 January, prior to maximum light, the star was already in outburst and was emitting $\sim 12$ times more Hα flux than in its qui-
escent state. This 2004 August flux from the 
HST image is consistent with the declining fluxes 
derived from the integrated spectral line profiles 
from 2003 through 2004 (see §2.2).

The outburst H\(\alpha\) flux is likely originating in the 
dense, optically thick wind from the star. But, 
can we really consider this a LBV nebula? The 
relatively strong [N II] lines do imply the presence 
of circumstellar gas, as does the indication 
of CNO-processed material in the wind. However, 
a normal LBV eruption does not generally result 
in the ejection of a massive shell, or nebula, in 
the first place. If SN 2002kg is similar to S Dor, 
then we might expect any nebula to be quite comp-
act. Based on HST imaging, Weis (2003) places 
an upper limit on the S Dor nebula diameter of 
0.25 pc. Similarly, we find that the source is un-
resolved (\(\leq 1.8\) WFC1 pixels FWHM) in the 2004 
August HST F658N image which, at the distance 

\[\text{to NGC 2403 (3.13 Mpc; Freedman et al. 2001), implies a diameter } \leq 1.4 \text{ pc for the nebula. If the} \]
wind has been expanding at a constant \(370 \text{ km s}^{-1}\) between 2002 Oct 26 and 2004 Aug 17, this 
implies that the wind-blown shell, or nebula, is 
only \(\sim 0.001 \) pc in diameter. We infer that the 
detected H\(\alpha\) emission is from the ejecta of the 
recent eruption.

5. DISCUSSION AND CONCLUSIONS

We have shown that SN 2002kg in NGC 2403 is 
unlike a typical Type II, core-collapse SN, given 
both its spectroscopic and photometric properties. 
Although spectroscopically SN 2002kg re-
sembles the SNe IIn, the ejecta expansion velocity, 
\(\sim 370 \text{ km s}^{-1}\), is much lower than what is observed 
for the prototypical SNe IIn (e.g., SN 1988Z; Tu-
ratto et al. 1993). Additionally, the star increased 
only \(\sim 2 \text{ mag in } V\). We deduce, therefore, that 
SN 2002kg is, in fact, not a genuine SN (strictly 
defined as the explosion of a star at the end of its 
life), but instead represents an eruption of a nor-
mal, or “classical,” supergiant LBV star, possibly 
alogous to S Dor. With \(M_{\text{bol}} \approx -9.8 \text{ mag and} \]
\(\log T_{\text{eff}} \approx 4.19 \text{ for the precursor in its quiescent} \)
state, the star clearly lies on the “S Dor insta-



bility strip” (Wolf 1989; Humphreys & Davidson 
1994).

We further support this conclusion by show-
ing in Figure 12 the absolute light curve for SN 
2002kg, relative to the light curves for other SN 
impostors (SNe 1961V, 1954J/V12 1997bs and 
2000ch) in a similar vein as Van Dyk et al. (2000; 
their Figure 6). Although the bandpasses through 
which these light curves were generated differ 
from one object to the other, the relative similar-
ities in luminosity, energy, and variability argue 
strongly that SN 2002kg is also a SN impostor.

SN 2002kg appears from its light curve to be the 
least energetic example of a SN impostor 
known so far. SNe 1954J/V12, 1961V, and \(\eta\) Car 
may represent the high-energy end of a pre-SN 
super-outburst phase, with SN 1997bs and SN 
2000ch somewhere in between. The lower ener-
getics can also be seen in a comparison (Fig. 13) 
of the early-time spectra of SNe 2002kg, 1997bs, 
and 2000ch. The overall strength of the Balmer-
line profiles in SN 2002kg is lower than in the 
other two SNe. Moreover, the bases of the pro-
files in SN 2002kg are not nearly as broad as 
in SNe 1997bs and 2000ch, consistent with the 
lower ejecta velocities in SN 2002kg. (SN 2000ch 
also shows more of a true P-Cygni profile, with 
shallow blue absorption troughs in the Balmer 
lines.)

SN 2002kg is clearly less energetic than SN 
1954J/V12 in the same host galaxy, NGC 2403; 
this is reflected both in the lower expansion ve-
locity (\(\sim 370 \text{ km s}^{-1}\), versus \(\sim 700 \text{ km s}^{-1}\) at age 
\(\sim 50 \yr\); Van Dyk et al. 2005), and fainter appar-
rent brightness (\(m_V[\text{max}] \approx 18.3 \text{ mag versus } 16.1 \)
mag; Humphreys & Davidson 1994).

The precursor of SN 2002kg is the irregular 
blue variable star V37 in NGC 2403, identified by 
Humphreys & Aaronson (1987) and Humphreys 
& Davidson (1994) as a LBV. We have also di-
rectly placed constraints on the initial mass of 
this precursor to be \(\gtrsim 40 \MSun\). As a result of the 
outburst, the star became redder and attained a 


nearly constant color (the \(B - V\) color remained 
relatively unchanged for nearly 1.5 yr; the over-
all constant shape of the spectral continua fur-
ther supports this), as the pseudo-photosphere of 
the optically thick envelope expands. The absolu-
ute flux in the H\(\alpha\) line decreased between early 
2003 and late 2004; this is also reflected in the 
\(B - R\) color of the star (0.41 mag in 2003 March 
and 0.26 mag in 2004 August/September). The 
constant color argues against any dust formation 
event for SN 2002kg/V37, such as is evident in the 
Homunculus around \(\eta\) Car and in SN 1954J/V12 
(Van Dyk et al. 2005), although dust might form 
later for the SN 2002kg/V37 ejecta.

SN 2002kg/V37 is one of a growing number of 
objects which “impersonate” SNe IIn. These im-
impostors exhibit a broad range of properties and
actually represent a pre-SN evolutionary phase of very massive stars. It is imperative to continue monitoring the star to detail its further evolution. Other recent, less well-studied cases, such as SN 1999bw in NGC 3198, SN 2001ac in NGC 3504, and SN 2003gm in NGC 5334, also require detailed study, to provide valuable additional examples of this rare phenomenon and improve our understanding of massive-star evolution.

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Table 1

KAIT Photometry of SN 2002kg

| UT date     | JD−2450000 | $R$ (mag) |
|-------------|------------|-----------|
| 1998 Nov 13 | 1130       | $\geq 19.5$ |
| 2002 Oct 26.56 | 2574.06   | 18.4(0.1) |
| 2002 Nov 01.53 | 2580.03   | 18.3(0.1) |
| 2002 Nov 12.54 | 2591.04   | 18.1(0.2) |
| 2002 Nov 16.44 | 2594.94   | 18.4(0.1) |
| 2002 Nov 20.40 | 2598.90   | 18.4(0.2) |
| 2002 Dec 02.49 | 2610.99   | 18.0(0.1) |
| 2003 Jan 08.40 | 2647.90   | 17.9(0.1) |
| 2003 Jan 16.29 | 2655.79   | 18.0(0.1) |
| 2003 Jan 26.34 | 2665.84   | 18.2(0.1) |
| 2003 Jan 31.27 | 2670.77   | 18.2(0.1) |
| 2003 Feb 08.26 | 2678.76   | 18.1(0.1) |
| 2003 Feb 23.23 | 2693.73   | 18.1(0.1) |
| 2003 Mar 03.20 | 2701.70   | 18.0(0.1) |
| 2003 Mar 08.17 | 2706.67   | 18.1(0.1) |
| 2003 Mar 13.21 | 2711.71   | 17.8(0.1) |
| 2003 Mar 25.17 | 2723.67   | 18.0(0.1) |
| 2003 Oct 11.49 | 2923.99   | 18.1(0.1) |
| 2003 Oct 18.54 | 2931.04   | 18.3(0.1) |
| 2003 Oct 26.54 | 2939.04   | 18.0(0.1) |
| 2003 Nov 10.53 | 2954.03   | 18.1(0.1) |
| 2003 Nov 23.48 | 2966.98   | 18.1(0.1) |
| 2004 Feb 01.32 | 3036.82   | 18.5(0.1) |
| 2004 Feb 11.26 | 3046.76   | 18.8(0.1) |
| 2004 Mar 03.19 | 3068.69   | 19.1(0.3) |
| 2004 Mar 08.13 | 3073.63   | 19.4(0.2) |
| 2004 Mar 17.16 | 3082.66   | 18.7(0.1) |
| 2004 Apr 04.20 | 3099.70   | 18.4(0.1) |

Uncertainties in the magnitudes are given in parentheses.
### Table 2
SN 2002kg Photometry from Other Sources

| UT date      | U (mag) | B (mag) | V (mag) | R (mag) | I (mag) | Source  |
|--------------|---------|---------|---------|---------|---------|---------|
| 1987 Feb 04  | · · ·   | ≥ 20.3  | ≥ 20.4  | ≥ 20.1  | · · ·   | JKT     |
| 1992 Mar 22  | · · ·   | ≥ 16.0  | ≥ 15.8  | ≥ 15.7  | · · ·   | INT     |
| 1997 Oct 13  | 19.59(04) | 20.55(03) | 20.63(04) | 20.54(02) | 20.69(03) | NOT     |
| 1998 Oct 05  | · · ·   | ≥ 20.5  | · · ·   | ≥ 20.4  | · · ·   | JKT     |
| 1999 Apr 25  | · · ·   | ≥ 20.1  | · · ·   | ≥ 20.1  | · · ·   | JKT     |
| 2003 Mar 26  | · · ·   | 18.45(03) | 18.32(04) | 18.04(02) | 17.97(02) | P60     |
| 2004 Aug 17\(^b\) | · · ·   | 19.58(05) | 19.39(06) | · · ·   | 19.21(06) | HST     |
| 2004 Sep 21\(^b\) | · · ·   | 19.41(07) | · · ·   | 19.13(04) | · · ·   | HST     |

Note: uncertainties of hundredths of a magnitude are indicated in parentheses.

\(^a\)JKT=Johannes Kepler Telescope; INT=Isaac Newton Telescope; NOT=Nordic Optical Telescope; P60=Palomar 1.5-m telescope; HST=Hubble Space Telescope.

\(^b\)Transformed from the flight system magnitudes via synthetic photometry of normal stars with SYNPHOT; see text.

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Fig. 1.— SN 2002kg (indicated by tick marks) in NGC 2403 in an unfiltered (∼ R) image obtained with the Katzman Automatic Imaging Telescope (KAIT) 0.76-m telescope on 2002 October 26. The image is 6′6 × 6′6 in size. North is up, and east is to the left.
Fig. 2.— The unfiltered (∼ $R$-band) light curve (open squares) of SN 2002kg obtained using KAIT. (See Table 1; see text regarding the photometric zero point and systematic errors in the light curve.) Also shown are the $R$-band data for the SN obtained with the Palomar 1.5-m telescope on 2003 March 26.15 (filled square) and with the HST ACS on 2003 September 21.07 (filled triangle). The photometry has been corrected for extinction (see text) and for the true distance modulus of the host galaxy, NGC 2403 (Freedman et al. 2001).
Fig. 3.— SN 2002kg (indicated by the arrow) in a V-band image obtained at the Palomar 1.5-m telescope on 2003 March 26.15.

Fig. 4.— SN 2002kg (indicated by the arrow) in a F606W image obtained with the ACS/WFC on-board HST on 2004 August 17.11. This figure is to approximately the same scale and orientation as Figure 3. Note that the SN field is near the edge of the ACS image.

Fig. 5.— Spectra of SN 2002kg obtained at the 10-m Keck telescope (2003 Jan 6, 2003 Nov 29, and 2004 Dec 12) and the 6.5-m MMT (2003 Nov 20).
Fig. 6.— A comparison of the spectra shown in Figure 5 in the wavelength region containing Hα and the [N II] lines. The narrow emission component of Hα is unresolved, and the broad component remains relatively constant in width throughout 2003 and 2004. The prominent, unresolved [N II] λ6548, 6584 Å emission lines suggest the presence of N-enhanced circumstellar material.
Fig. 7.— Expanded views of the spectra of SN 2002kg shown in Figure 5 (redshift-corrected assuming $z = 0.000437$), in the blue wavelength region. Also shown for comparison are spectra of the LBVs AG Car (Walborn & Fitzpatrick 2000) and S Dor (Massey 2000; redshift-corrected assuming $z = 0.000927$). Various lines are labelled.

Fig. 8.— The precursor of SN 2002kg (indicated by the arrow), as seen in a $V$-band image of the host galaxy, NGC 2403, obtained with the 2.6-m Nordic Optical Telescope (NOT) on 1997 Oct 13 (Larsen & Richtler 1999). This figure is to nearly the same scale and orientation as in Figure 3. The location of the precursor is coincident with the irregular blue variable V37, reported by Tammann & Sandage (1968).
Fig. 9.— The (a) $(U - B, B - V)$ and (b) $(B - V, V - I)$ color-color diagrams of SN 2002kg and its stellar environment (within $\sim 500$ pc). The colors of the precursor star (filled circle) measured from the NOT images are shown in both diagrams. The open squares represent the colors of the stars in the environment measured from the NOT images for panel (a) and the HST ACS/WFC images for panel (b) (after transformation from flight system to standard Johnson-Cousins colors). Also shown are the loci for supergiant (long-dashed line) and main sequence (short-dashed line) stars, as well as the reddening vector (solid line) from $A_V = 0$ to $A_V = 3$ mag, assuming the Cardelli et al. (1989) reddening law. From these diagrams, we infer $A_V = 0.6 \pm 0.2$ mag for the precursor star. In (b) we show the colors of the SN during outburst from the 2003 Palomar data (filled square) and from the 2004 HST/ACS data (filled triangle; the open triangle represents the SN colors after an assumed correction for contamination by the strong H$\alpha$ emission in the F606W band; a dotted line connects the two symbols).
Fig. 9.— (Continued.)
Fig. 10.— HR diagrams, showing the locus for the precursor (five-pointed star), after correction for reddening and the true distance modulus of the host galaxy, NGC 2403, and assuming that $M_{\text{bol}}$ has remained constant before outburst and at maximum. Also shown for comparison are the model stellar evolutionary tracks from Lejeune & Schaerer (2001), with enhanced mass loss, for 120 $M_\odot$ (dotted line), 85 $M_\odot$ (short-dashed line), 60 $M_\odot$ (solid line), and 40 $M_\odot$ (long-dashed line). Panel (a) shows the tracks for solar metallicity ($Z = 0.02$), and panel (b) shows the tracks for sub-solar metallicity ($Z = 0.008$).
Fig. 10.— (Continued.)
Fig. 11.— The continuum-subtracted Hα image of the host galaxy, NGC 2403, obtained with the 2.6-m Nordic Optical Telescope (NOT) on 1997 Oct 13 (Larsen & Richtler 1999), showing net emission surrounding the precursor of SN 2002kg (indicated by the arrow). This figure is shown to the same scale and orientation as Figure 8. The nebula in this image is spatially unresolved, with diameter $\lesssim 14$ pc (FWHM). The Hα luminosity is consistent with photoionization by a single blue supergiant star. Artifacts, due to incomplete continuum subtraction, are also seen in the figure.

Fig. 12.— A comparison of the absolute light curve for SN 2002kg in NGC 2403 (filled triangles and solid line; also see Figure 2) with that of $\eta$ Car (dotted line), SN 1954J in NGC 2403 (long-dashed, dotted line), SN 1961V in NGC 1058 (short-dashed, dotted line; adapted from Humphreys, Davidson, & Smith 1999), SN 1997bs in M66 (short-dashed line; Van Dyk et al. 2000), and SN 2000ch in NGC 3432 (long-dashed line; Wagner et al. 2004). We note that the bandpasses through which each of these light curves were generated differed from one object to the other.
Fig. 13.— A comparison of the early-time optical spectrum of SN 2002kg (see Figure 5; redshift-corrected assuming $z = 0.000437$) with those of SN 1997bs in M66 (Van Dyk et al. 2000; redshift-corrected assuming $z = 0.002425$) and SN 2000ch in NGC 3432 (Wagner et al. 2004; redshift-corrected assuming $z = 0.002055$).
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