On the Progenitor of the Type II Supernova 2004et in NGC 6946[1]

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ABSTRACT. Supernova (SN) 2004et is the eighth historical SN in the nearby spiral galaxy NGC 6946. Here we report on early photometric and spectroscopic monitoring of this object. SN 2004et is a Type II event, exhibiting a plateau in its light curves, but its spectral and color evolution appear to differ significantly from those of other, more normal Type II plateau (II-P) SNe. We have analyzed Canada-France-Hawaii Telescope images of the host galaxy taken prior to the SN explosion, identifying a candidate progenitor for the SN. The star's absolute magnitude and intrinsic color imply that it was a yellow, rather than red, supergiant star, with an estimated zero-age main-sequence mass of $15^{+5}_{-2}\,M_{\odot}$. Although this mass estimate is consistent with estimates and upper limits for the progenitors of other, more normal SNe II-P, the SN 2004et progenitor's unusual color could further imply a preexplosion evolutionary history analogous to, but less extreme than, that for the progenitors of the peculiar Type II-P SN 1987A or the Type IIb SN 1993J. The identity of the progenitor candidate needs to be verified when the SN has significantly dimmed.

1. INTRODUCTION

The identification of the progenitors of supernovae (SNe) provides direct information on their explosion mechanisms, a key issue in studies of SNe. The white dwarfs thought to give rise to SNe Ia have such exceedingly low luminosities that they cannot be detected in other galaxies, and a direct identification of a possible binary companion has yet to be made (but see Ruiz-Lapuente et al. 2004). Core-collapse SNe, on the other hand, come from more luminous, massive stars. Unfortunately, even these progenitors are so faint that detection (ground- or space-based) is confined to the most nearby galaxies, in which SN discoveries are relatively rare. Up to now, only half a dozen SNe have had their progenitors identified: SN 1961V in NGC 1058 (Zwicky 1964, 1965), SN 1978K in NGC 1313 (Ryder et al. 1993), SN 1987A in the Large Magellanic Cloud (LMC; e.g., Gilmozzi et al. 1987; Sonneborn et al. 1987), SN 1993J in NGC 3031 (M81; Aldering et al. 1994; Cohen et al. 1995), SN 1997bs in NGC 3627 (M66; Van Dyk et al. 1999, 2000), and SN 2003gd in NGC 628 (M74; Van Dyk et al. 2003c; Smartt et al. 2004). It should be noted that all of these core-collapse SNe were somewhat unusual, except for the normal Type II SN 2003gd.

In addition, the normal Type II-P SN 2004dj in NGC 2403 was found to occur at a position coincident with a compact star cluster (Maíz-Apellániz et al. 2004). By studying the stellar

population and the age of the cluster, an estimate of a main-sequence mass of $15\,M_{\odot}$ for the SN progenitor was made. Tentative identification and upper mass limits are also derived for several other SNe (Van Dyk et al. 2003a, 2003b; Leonard et al. 2002a, 2003; Smartt et al. 2001, 2002).

Here we attempt to identify the progenitor of the Type II SN 2004et in NGC 6946. The SN was discovered by S. Moretti (see Zwitter et al. 2004) at about 12.8 mag on unfiltered CCD images taken with a 0.4 m telescope on September 27 (UT dates are used throughout this paper), with a reported position of $\alpha = 20^{\rm h}35^{\rm m}25\overset{\rm s}{.}33$, $\delta = +60°07'17\overset{''}{.}7$ (J2000.0). A high-resolution optical spectrum (Zwitter et al. 2004) suggested that SN 2004et is a Type II event, which was subsequently confirmed by a low-resolution optical spectrum (Filippenko et al. 2004). We note that the host galaxy, NGC 6946 (Arp 29), a nearly face-on ($i \approx 29°\!\!.5$), starbursting spiral galaxy at relatively low Galactic latitude ($b \approx 11°\!\!.5$), is an especially prodigious SN producer: SN 2004et is the eighth historical SN (including SNe 1980K and 2002hh) in this galaxy.

The explosion date of SN 2004et is well constrained. Yamaoka et al. (2004) reported that nothing was detected to a limiting magnitude of 18.5 at the position of SN 2004et on September 19.655. They also reported that NGC 6946 was imaged frequently by the robotic TAROT telescope. The SN was not detected on September 22.017 (limiting magnitude 19.4 ± 1.2), but was detected at 15.17 ± 0.16 mag on September 22.983, only about 1 day later. The SN then brightened to 12.7 ± 0.3 mag on September 25.978. We use September 22.0 (JD 2,453,270.5) as the time of explosion for SN 2004et throughout this paper.

A preliminary study of the progenitor of SN 2004et, based on images taken with the 0.9 m Kitt Peak telescope (see Van

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TABLE 1
PHOTOMETRY OF THE COMPARISON STARS FOR SN 2004et

ID	U	B	V	R	I	u'	g'	r'
1	...	18.31(03)	17.09(02)	16.41(02)	...	...	17.66(04)	16.67(03)
2	...	19.44(04)	18.29(03)	17.60(02)	...	...	18.82(05)	17.90(04)
3	...	19.30(03)	18.45(03)	18.00(03)	...	...	18.82(04)	18.19(04)
4	...	18.40(02)	17.65(02)	17.22(02)	...	...	17.97(03)	17.43(03)
5	...	18.31(02)	17.37(02)	16.87(01)	...	...	17.79(03)	17.07(03)
6	...	18.26(02)	17.46(02)	17.00(02)	...	...	17.80(03)	17.21(03)
7	16.62(03)	15.49(02)	14.18(02)	13.44(01)	12.71(02)	17.38(04)	14.79(03)	13.72(03)
8	16.54(03)	15.54(02)	14.33(02)	13.62(01)	12.93(03)	17.32(04)	14.90(03)	13.92(03)

NOTE.—Uncertainties in the last two digits are indicated in parentheses.

Dyk et al. 1996), was reported by Li et al. (2004a). These images were taken under relatively poor conditions (a seeing of about 2″.7) and with low resolution (0″.863 pixel^{-1}). A faint object, considered possibly extended, was detected at the position of SN 2004et in the *R*-band image, although the high measured luminosity of the object led to the suggestion that it might be a star cluster, rather than a single star. An analysis of deeper, higher resolution (binned to 0″.412 pixel^{-1}) images taken under better seeing conditions (∼0″.8) with the Canada-France-Hawaii Telescope (CFHT) was also reported by Li et al. (2004b). Their revised luminosity of the progenitor was consistent with a massive supergiant, although it was likely too bright and too blue for a single red supergiant.

In this paper we analyze the best available CFHT images of the site of SN 2004et in detail, and the results here supersede those reported by Li et al. (2004b). Section 2 describes spectroscopic and photometric observations of SN 2004et itself. Section 3 describes our analysis of these pre-SN CFHT images. A discussion of the likely nature of the SN progenitor, based on this analysis, is presented in § 4, and our conclusions are summarized in § 5.

2. OBSERVATIONS OF SN 2004et

From the early photometric and spectroscopic observations of SN 2004et, we can get at least an initial indication of its nature.

SN 2004et has been monitored in the Johnson-Cousins *UBVRI* system with the 0.76 m Katzman Automatic Imaging Telescope (KAIT; see Li et al. 2000; Filippenko et al. 2001) at Lick Observatory since its discovery. The images were reduced using standard aperture photometry in the IRAF[5] DAO-PHOT package (Stetson 1987), and transformation to the standard Johnson-Cousins *UBVRI* system was performed using the local comparison stars listed in Table 1 (see Li et al. 2001 for more details). Figure 1 shows an *I*-band image of the SN, with these comparison stars labeled. The final photometry for SN 2004et is listed in Table 2, while Figure 2 shows the light curves of SN 2004et (*filled circles*), along with comparisons
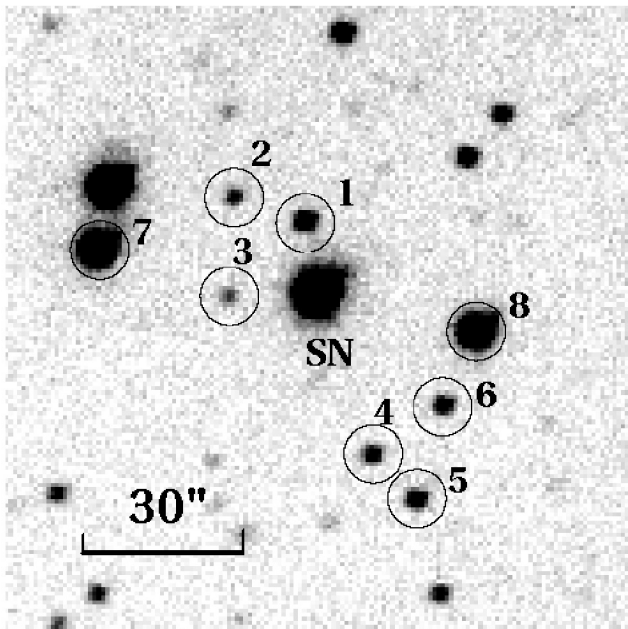
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[5] IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

FIG. 1.—A 2′ × 2′ section of the KAIT *I*-band image taken on September 30 of SN 2004et in NGC 6946. The local photometric comparison stars in the field of SN 2004et are labeled (see Table 1). North is up and east is to the left.

TABLE 2
PHOTOMETRY OF SN 2004et

JD −2,450,000	U	B	V	R	I
3278.75	12.17(01)	12.89(01)	12.67(03)	12.34(04)	12.10(04)
3280.71	12.20(02)	12.91(01)	12.65(01)	12.33(02)	12.09(01)
3284.65	12.32(06)	12.97(01)	12.66(03)	12.31(02)	12.07(03)
3287.66	12.45(03)	13.01(02)	12.68(03)	12.30(02)	12.04(03)
3288.66	12.56(08)	13.03(01)	12.68(04)	12.29(02)	12.01(02)
3290.65	12.66(02)	13.08(02)	12.68(04)	12.27(02)	12.00(03)
3292.65	12.82(04)	13.13(01)	12.67(02)	12.27(02)	11.98(02)
3294.66	12.96(05)	13.22(01)	12.67(03)	12.26(02)	11.97(02)

NOTE.—Uncertainties in the last two digits are indicated in parentheses.
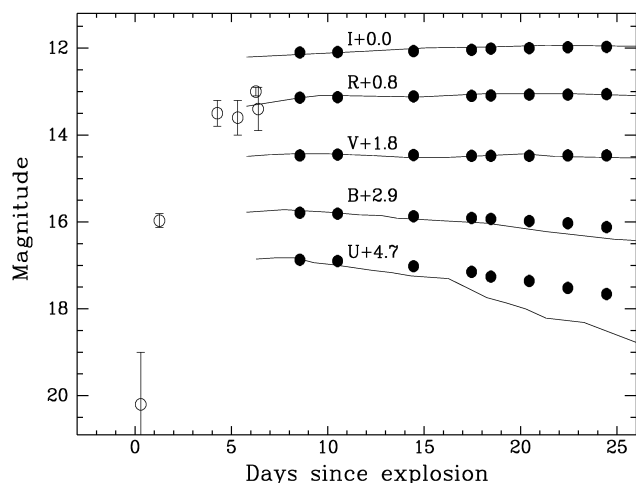
FIG. 2.—*UBVRI* light curves of SN 2004et. The curves have been shifted by the amount indicated. Also shown are light curves of SN 1999em (*solid lines*), shifted arbitrarily to match these of SN 2004et. The prediscovery *R*-band magnitudes of SN 2004et reported by A. Klotz and collaborators (see Yamakoa et al. 2004) are plotted as open circles.

FIG. 3.—Color curves of SN 2004et (*symbols*) are visually matched to those of SN 1999em (*lines*). The colors of SN 1999em have been dereddened by $E(B - V) = 0.10$ mag, while the curves of SN 2004et are shifted by 0.0, -0.46, -0.35, and -0.28 mag, for the $U - B$, $B - V$, $V - R$, and $V - I$ colors, respectively. See text for more details.

to the typical Type II-P SN 1999em (*lines*; Leonard et al. 2002b). The prediscovery *R*-band magnitudes reported by Yamaoka et al. (2004) are also shown. The light curves of SN 1999em have been shifted arbitrarily by eye to match those of SN 2004et. The two SNe have rather similar light curves in the *V*, *R*, and *I* bands, suggesting that SN 2004et is a relatively normal SN II-P. However, SN 2004et appears to evolve more slowly than SN 1999em in the *U* and *B* bands.

The color curves of SN 2004et are shown in Figure 3 (*symbols*), along with comparisons to SN 1999em (*lines*; Leonard et al. 2002b). The colors of SN 1999em were dereddened by the estimated extinction of $E(B - V) = 0.10$ mag, following the reddening law in Schlegel et al. (1998). The color curves of SN 2004et were shifted by eye to match those of SN 1999em, and the best fit was found when the curves were shifted 0.0, -0.46, -0.35, and -0.28 mag for the $U - B$, $B - V$, $V - R$, and $V - I$ colors, respectively. If we assume SNe 2004et and 1999em have the same color evolution, the offsets in these color curves suggest an $E(B - V)$ color excess for SN 2004et of 0.0, 0.46, 0.55, and 0.20 mag, respectively. The $B - V$ curve yields a color excess that is consistent with the value derived from high-resolution spectroscopy [$E(B - V) = 0.41$ mag; see § 3]. The color evolution of SNe 2004et and 1999em clearly differ from each other. In particular, the $U - B$ and $B - V$ colors of SN 2004et evolve more slowly than those of SN 1999em, in agreement with the trend seen in the *UB* light curves.

We have obtained two optical spectra of SN 2004et using the Lick Observatory 3 m Shane telescope with the Kast double spectrograph (Miller & Stone 1993) on 2004 October 1 and 12, which was 9 and 20 days after the SN explosion, respectively. The journal of observations is listed in Table 3. The data were reduced using standard techniques as described by
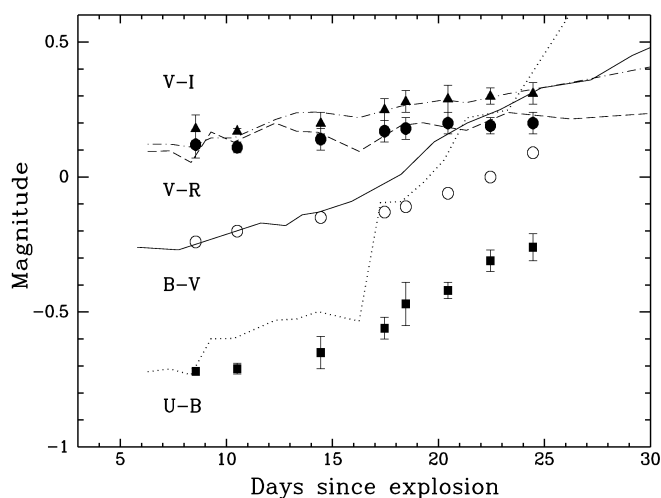
Li et al. (2001 and references therein). Flat fields for the red CCD were taken at the position of the object to reduce near-IR fringing effects. The spectra were corrected for atmospheric extinction and telluric bands (Bessell 1999; Matheson 2000) and then flux calibrated using standard stars observed at similar air mass on the same night as the SN.

Figure 4 shows the spectra of SN 2004et, with a comparison to SN 1999em at similar epochs (Hamuy et al. 2001). All spectra of SN 1999em have been dereddened by $E(B - V) = 0.10$ mag (Leonard et al. 2002b), and all spectra of SN 2004et have been dereddened by $E(B - V) = 0.41$ mag (see § 3). The spectra have also been corrected for the redshift of the SN host galaxy ($z = 0.000160$ for SN 2004et, and $z = 0.002392$ for SN 1999em). The spectra of SN 2004et show some clear differences and peculiarities relative to SN 1999em. The spectrum at 9 days after explosion has an overall bluer continuum than that of SN 1999em in the range of 4000–10000 Å, and there is a peculiar decline blueward of 4000 Å not commonly observed in the spectra of normal SNe II-P. The P Cygni–like profile of Hα is dominated by the emission component, al-

TABLE 3
JOURNAL OF SPECTROSCOPIC OBSERVATIONS OF SN 2004et

UT Date	t^a	Telescope	Range[b] (Å)	Air Mass[c]	Slit (arcsec)	Exposure (s)
2004 Oct 1	+9	Lick 3 m	3300–10500	1.1	2.0	240
2004 Oct 12	+20	Lick 3 m	3300–10500	1.1	2.0	240

[a] Days since explosion (assumed to be September 22.0 UT, JD 2,453,270.5), rounded to the nearest day.
[b] Observed wavelength range of spectrum.
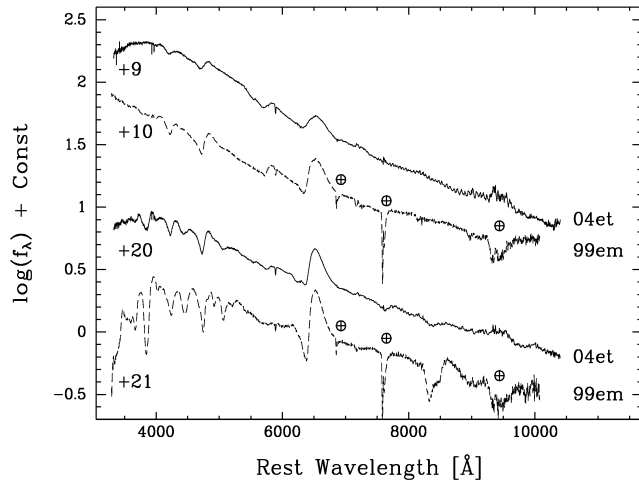[c] Average air mass of observations.

Fig. 4.—Comparison of the SN 2004et spectra (*solid lines*) to SN 1999em (*dashed lines*) at similar epochs. The spectra have been corrected for reddened and host-galaxy redshift (see text for details). The telluric lines in the SN 1999em spectra are marked.

though the other H Balmer lines have more typical P Cygni profiles. An additional absorption feature appears to be present just blueward of the He I/Na I D absorption at 5700 Å.

The SN 2004et spectrum at 20 days after explosion is also bluer than that of SN 1999em. A shallow absorption trough, which appears to consist of two components, developed at the absorption component of the P Cygni profile of Hα, but the emission component is still predominant. By comparison, SN 1999em has a more typical P Cygni Hα profile. While strong Fe II lines appear at the blue end of the SN 1999em spectrum, these lines are less prominent in SN 2004et. Overall, SN 2004et seems to evolve more slowly than SN 1999em, especially in the UV part of the spectrum. This is consistent with the slower *UB* photometric evolution for SN 2004et, discussed above.

Clearly, SN 2004et is of Type II and (presumably) is a core-collapse SN. However, we conclude that although SN 2004et shows a plateau in its light curve (Fig. 2), it displays noticeable peculiarities in both its spectroscopic and photometric properties when compared to the canonical SN II-P. The relative blue colors and weak P Cygni absorption features of SN 2004et may indicate the presence of a circumstellar interaction (dis-

cussed more in § 4). More data for the SN from continuing follow-up observations will provide additional information on the nature and evolution of SN 2004et.

3. PRESUPERNOVA IMAGES

Images of NGC 6946 containing the SN 2004et site were obtained by one of the authors (J. C. C.) with the CFHT on two occasions prior to the explosion: (a) broadband *B*, *V*, and *R* images were obtained with the CFH12K mosaic camera on 2002 August 6, and (b) Sloan u', g', and r' images were obtained with the MegaCam camera on 2003 October 23. A summary of these pre-SN CFHT data is given in Table 4. The 2 × 2 binned images of data set (a) were those analyzed and reported by Li et al. (2004b). Here we analyze the full-resolution (unbinned) images. Both the CFH12K and MegaCam cameras have large fields of view. To facilitate the analysis, only the image sections that contain the SN site are studied here. For data set (a), a section of 6'.8 × 6'.8 around SN 2004et is considered, while for data set (b), the section is 2'.5 × 2'.5 around the SN site.

It is essential to locate with high astrometric precision the SN site in the CFHT images. We have adopted two methods for this purpose: an astrometric solution and image-to-image registration. For our first approach, we use several images of SN 2004et obtained with KAIT and derived astrometric solutions based on the accurate positions for stars in the USNO-A2.0 catalog seen in the SN 2004et field. We have measured an accurate position for the SN of $\alpha = 20^{\rm h}35^{\rm m}25{\rm s}37$, $\delta = +60°07'17''8$ (J2000.0), with a total uncertainty of about 0''2. This is in excellent agreement (differing by 0''07 in α and 0''1 in δ) with the position measured from the radio observations (Stockdale et al. 2004).

We apply exactly the same procedure to the pre-SN CFHT images and inspect the immediate site of SN 2004et. We identify an apparent stellar object at the position of SN 2004et, particularly in the *R*, g', and r' images. The position of this object, measured from the best-seeing r' image, is $\alpha = 20^{\rm h}35^{\rm m}25{\rm s}38$, $\delta = +60°07'18''0$ (J2000.0), again with a total uncertainty of about 0''2. This position is very consistent (differing by 0''07 in α and 0''2 in δ) with that measured for the SN from the KAIT images, to within the uncertainties.

For the image registration approach, we choose the best available KAIT image, detect all the stars with sufficient signal-to-noise ratio, and output their (x, y) positions to a list. The same is done for the CFHT images. The two sets of star lists are then used to solve for the geometrical transformation between the two sets of images. In essence, both of our approaches are quite similar, the difference being that image registration finds the geometrical match between images directly, whereas the astrometric solution uses an external reference frame (the USNO-A2.0 catalog). We therefore might expect the image registration method to perform somewhat better, since two images are directly compared.

TABLE 4
Summary of CFHT Observations

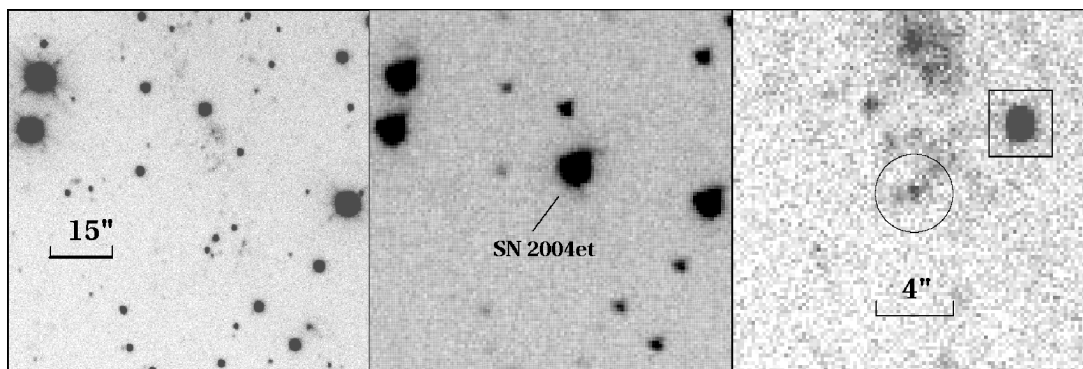| Date (UT)	Filter	Exposure (s)	Pixel Scale (arcsec)	Seeing (arcsec)
2002 Aug 6	*B*	90 × 5	0.206	0.8
2002 Aug 6	*V*	60 × 5	0.206	0.8
2002 Aug 6	*R*	60 × 5	0.206	0.8
2003 Oct 23	u'	90 × 5	0.185	0.7
2003 Oct 23	g'	60 × 5	0.185	0.8
2003 Oct 23	r'	30 × 5	0.185	0.6

Fɪɢ. 5.—*Left*: Pre-SN CFHT *R*-band image of NGC 6946. This image has been carefully registered to the KAIT *I*-band image of the SN shown in the central panel. North is up and east is to the left. *Right*: The SN environment in the CFHT image shown in greater detail. To guide the eye, the 2″ radius circle is centered on the SN position mapped from the KAIT image, although the uncertainty in the measured SN position is much smaller (0″.2). An apparent stellar object is seen near the exact center of the circle. The bright star used to measure relative offsets is marked by a square (see text for details).

Figure 5 shows the results from the image registration method when the CFHT *R*-band image is compared to the KAIT *I*-band image shown in Figure 1. The geometrical solution has a rms of about 0″.1. When the position of the SN measured from the registered KAIT image is mapped onto the CFHT image, it is offset from the object we identify by only 0″.08. As shown in the right panel of Figure 5, the progenitor star is right in the middle of the 2″ radius circle centered on the SN position. (Such a large circle is shown only to guide the eye; we measured the SN position with a much lower uncertainty of about 0″.2.)

At the distance of NGC 6946, the uncertainty in the SN position (0″.2) corresponds linearly to ~5 pc, a radial scale in a normal, star-forming spiral galaxy within which many massive stars could exist. However, we note that no other luminous stellar sources are detected within the 0″.2 error circle of the SN position. The possibilities then are that either the star we identify here is the progenitor of SN 2004et, or else the progenitor is not detected in the CFHT images. It is also possible that the object we have identified is actually a compact star cluster. Further discussion of these various possibilities is given in § 4. However, at least for the sake of argument, we assume hereafter that the identified star is the progenitor of SN 2004et. We further investigate its luminosity and color from the photometry to determine its nature.

Figure 6 shows the SN 2004et environment in all of the CFHT images. The progenitor is well detected in the *R*, *g′*, and *r′* images. It is also detected on the *V* image, but its profile is not well defined. The progenitor is marginally detected in the *B* image and may be only very tentatively detected in the *u′* image.

We derive instrumental magnitudes for the progenitor star via point-spread function (PSF) fitting photometry in IRAF/DAOPHOT. A PSF that varies linearly across the image is constructed for each frame using all available bright and isolated stars. Because of the relatively low Galactic latitude

($b \approx 11°5$) of NGC 6946, there are plenty of stars to sample the PSF across the field, and usually more than 20 stars are used. To reduce the contamination from neighboring stars, the PSF is first fitted and subtracted from the two stars seen adjacent to the progenitor in Figure 6. To avoid any possible random positional shifts in the PSF-fitting procedure, the progenitor's centroid is fixed using relative offsets from a nearby bright star (marked by a square in the right panel of Fig. 5) in the *R* and *r′* images, in which the progenitor is well detected. The model PSF is then fitted at this position, and the adopted instrumental magnitudes for the star are determined.

Since the progenitor is faint and is located in a rather complex region, the instrumental magnitudes resulting from IRAF/DAOPHOT may have rather large uncertainties. To establish a more realistic assessment of the true photometric uncertainty, we have applied a procedure that is similar to the Monte Carlo simulation performed by Riess et al. (1998): we first introduce artificial stars with the same brightness as the progenitor throughout the image and then photometrically recover these artificial stars using the PSF-fitting procedure. For each grid in the 21 × 21 pixel rectangle region centered on the progenitor, we superimpose an artificial star, for a total of 441 measurements. The photometric uncertainty is then calculated from the standard deviation for the ensemble of 441 measurements, the average of the photometric uncertainties from IRAF/DAOPHOT, and the standard deviation of the uncertainties output from IRAF/DAOPHOT, all added in quadrature.

Photometric calibrations of the NGC 6946 field in the *B*, *V*, *R*, and *I* filters were obtained on 2002 November 5, 2003 May 31, and 2003 June 1 with the Nickel 1 m reflector at Lick Observatory. Additional calibrations, including *U*, were obtained on 2004 October 12 and 14 with KAIT. However, the field has not been directly calibrated in *u′*, *g′*, and *r′*. Since the transformation between the Johnson-Cousins *UBVRI* and the Sloan *u′g′r′i′z′* photometric systems has been well studied (e.g., Fukugita et al. 1996; Krisciunas et al. 1998), we adopt the trans-
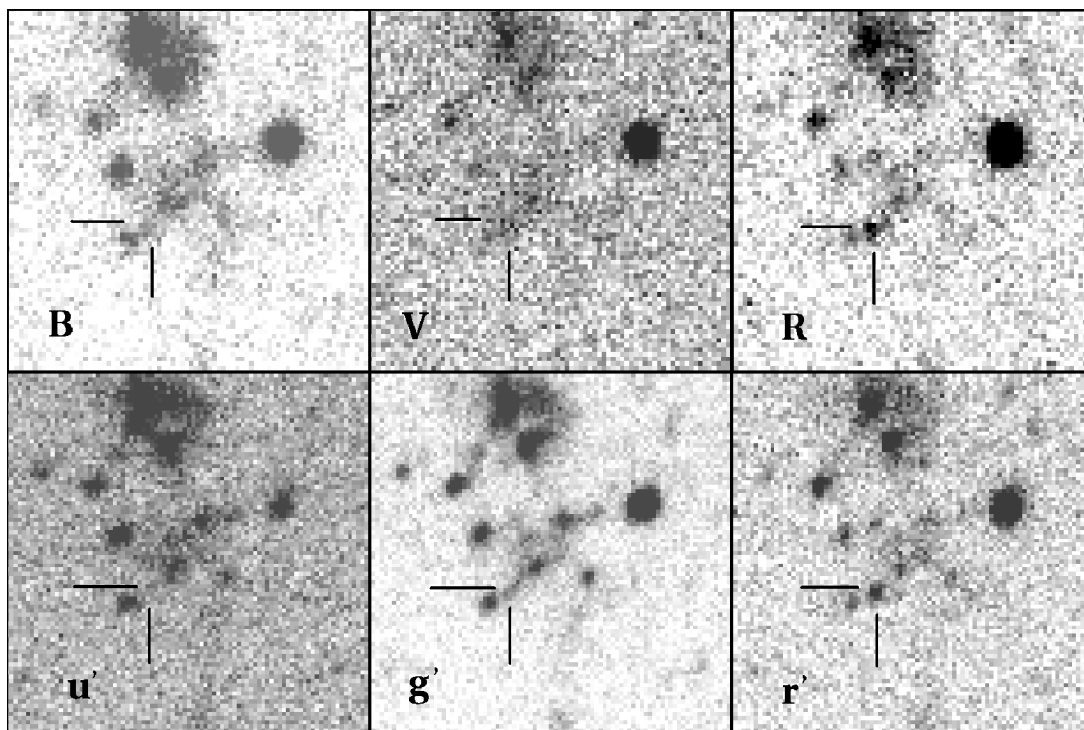
Fig. 6.—Comparison of $16'' \times 16''$ sections showing the area around SN 2004et in the CFHT $BVRu'g'r'$ images. North is up and east is to the left. The position of the progenitor is marked in each image.

formation from Krisciunas et al. (1998) to obtain the $u'g'r'$ cal-ibration for those CFHT images. The photometry for the local comparison stars in the Sloan bands is listed in Table 1. We have verified the transformation between the two photometric sys-tems, based on the stars in Table 1, and found the transformation to be satisfactory to ±0.03 mag.

The instrumental magnitudes of the progenitor are then trans-formed to the standard Johnson-Cousins and Sloan systems by performing relative photometry between the progenitor and the comparison stars in Table 1. Stars 1 through 6 are used for all the images except u', in which only stars 7 and 8 are sufficiently bright in the KAIT U images to provide a reliable transfor-mation. To compare the photometry from the two data sets, we transformed the $u'g'r'$ magnitudes of the progenitor to $UBVR$ and calculated the differences between the two sets of photom-etry. The apparent magnitudes for the progenitor in $UBVR$ are given in Table 5. The uncertainties in these magnitudes are based on the photometric uncertainty of the instrumental mag-nitudes, described above, and the standard deviation in the photometric calibration using the comparison stars, added in quadrature. The standard deviation in the transformation is also included for the $UBVR$ magnitudes converted from the $u'g'r'$ magnitudes.

An analysis of Table 5 suggests that the BVR magnitudes measured from the 2002 image set are consistently brighter than those transformed from the $u'g'r'$ magnitudes measured

from the 2003 image set. The differences are about 0.9, 2.1, and 1.6 σ for B, V, and R, respectively. While the differences are within the 3 σ uncertainties, the fact that all measurements from one data set are systematically brighter than the other is somewhat disconcerting. Several factors may have contributed to these differences: (1) the seeing and resolution are better for the $u'g'r'$ images, which could result in less background con-tamination and, therefore, overall fainter measurements; (2) the progenitor may be yellow in color (see below) and is relatively bright in V, and since there is not a good matching filter in the Sloan system for V, the transformation from the $g'r'$ magnitudes to V may be unreliable; and (3) the progenitor does not have a well-defined stellar profile in the V image (Fig. 6), and the

TABLE 5
Photometry of the SN 2004et Progenitor

Data Set	U	$\sigma(U)$	B	$\sigma(B)$	V	$\sigma(V)$	R	$\sigma(R)$
2002 Aug ……	…	…	24.30	0.48	22.93	0.31	22.50	0.18
2003 Oct[a] ……	25.12	0.58	24.84	0.39	23.70	0.20	22.93	0.20
	u'	$\sigma(u')$	g'	$\sigma(g')$			r'	$\sigma(r')$
2003 Oct …….	25.97	0.57	24.18	0.21			23.10	0.16

Note.—Photometry measured from the pre-SN CFHT images. See text for more details.

[a] The $u'g'r'$ magnitudes are converted to $UBVR$ magnitudes. See text for discussion of this transformation.

TABLE 6
Absolute Magnitude and Intrinsic Color of the SN 2004et Progenitor

Data Set	M_U^0	M_B^0	M_V^0	M_R^0
2002 Aug	...	-6.17 ± 0.69	-7.10 ± 0.55	-7.28 ± 0.48
2003 Oct	-5.62 ± 0.78	-5.63 ± 0.63	-6.33 ± 0.50	-6.85 ± 0.48
	$(U - B)_0$	$(B - V)_0$	$(V - R)_0$	$(B - R)_0$
2002 Aug	...	0.93 ± 0.58	0.18 ± 0.36	1.11 ± 0.53
2003 Oct	0.01 ± 0.70	0.70 ± 0.45	0.52 ± 0.28	1.22 ± 0.45

uncertainty in the *V* magnitude is underestimated, even with our extensive Monte Carlo experiments.

4. THE PROGENITOR OF SN 2004et

We can estimate the mass of the SN progenitor by comparing the intrinsic color and absolute magnitude of the object with stellar evolution tracks of massive stars having different zero-age main-sequence masses (M_{ZAMS}). In § 3 we discussed the apparent photometry for the progenitor (see Table 5). To estimate the absolute magnitude of the progenitor, we need to know the distance to NGC 6946 and have an estimate of the extinction toward SN 2004et. The distance to NGC 6946 is measured at $5.5^{+1.1}_{-0.9}$ Mpc from the H I Tully-Fisher relation (Pierce 1994), 5.4 Mpc from the CO Tully-Fisher relation (Schoniger & Sofue 1994), and 5.7 ± 0.7 Mpc from the expanding photosphere method for Type II SNe (Schmidt et al. 1994). Here we adopt 5.5 ± 1.0 Mpc for the distance. The relatively large uncertainty in the distance alone results in an uncertainty of ± 0.4 mag for the absolute brightness (luminosity) of stars in NGC 6946.

In § 2 we showed that SN 2004et and the typical SN II-P 1999em are unlikely to have the same color at a given age, and therefore a reliable extinction estimate for SN 2004et cannot be obtained from a comparison of the color curves for these two SNe. However, the high-resolution spectrum (Zwitter et al. 2004) shows distinct interstellar Na I absorption lines at heliocentric radial velocities of -21.1 ± 0.7 and $+45.2 \pm 0.4$ km s^{-1}, matching the expectation for a separate origin, respectively, within the Milky Way Galaxy and NGC 6946 (the systemic velocity of this galaxy is 48 km s^{-1}; NED[6]). The measured equivalent width of the Na I D lines corresponds to a total reddening of $E(B - V) = 0.41$ mag, following the calibration by Munari & Zwitter (1997). The Galactic component for the reddening alone is estimated to be $E(B - V) = 0.34$ mag (Schlegel et al. 1998). We adopt $E(B - V) = 0.41 \pm 0.07$ mag for the reddening toward SN 2004et, the lower limit of which corresponds to no host-galaxy reddening to SN 2004et within NGC 6946.

Correcting for the distance and extinction to SN 2004et, we derive the absolute magnitude and intrinsic color of the progenitor given in Table 6. To the best of our knowledge, no appropriate

stellar evolution tracks in the Sloan $u'g'r'i'z'$ system exist, so we are forced to consider only tracks in the Johnson-Cousins system. As a result of large uncertainties in the distance estimate and the photometry of the progenitor, the absolute magnitudes have quite large uncertainties as well (0.48–0.78 mag).

The color-magnitude diagrams (CMDs) of massive stars are significantly affected by the adopted metallicity, so we attempt to constrain the metallicity of the SN 2004et environment, as measured by other investigators. SN 2004et occurred at about $273''$ southeast of the nucleus of NGC 6946, or at $R/R_{25} \approx 0.8$. Zaritsky et al. (1994) published the metallicity and its radial gradient in NGC 6946, using the R_{23} method (Pagel et al. 1979). At the radial distance of SN 2004et, the relative oxygen abundance log (O/H) + 12 would be 8.84 dex, very close to the solar value (8.8 dex; Grevesse & Sauval 1998). However, Pilyugin et al. (2002) also determined the metallicity in NGC 6946, using the *P*-method (Pilyugin 2000). At the radial distance of SN 2004et, the relative oxygen abundance from the Pilyugin et al. measurement is 8.34 dex, which is only one-third solar. Since we consider both metallicity estimates to be equally valid, we use both of them in our analysis.

Figure 7 shows the CMDs for SN 2004et, compared with model stellar evolution tracks for a range of masses from Lejeune & Schaerer (2001), assuming enhanced mass loss for the most massive stars and solar metallicity ($Z = 0.02$). Figure 8 illustrates the results for a metallicity of $Z = 0.008$ (40% of solar). The open square shows the locus of the progenitor in the diagrams derived from the *BVR* images, while the filled square gives the locus from the $u'g'r'$ images.

From both Figures 7 and 8 we can rule out that the progenitor was a blue star (with the possible exception of the $[M_V^0, (V - R)_0]$ and $[M_R^0, (V - R)_0]$ CMDs measured from the 2002 CFHT data set, in which the $(V - R)_0$ color has a significantly larger uncertainty than that from 2003 data set). Both image data sets suggest, however, that the progenitor may in fact be a yellow supergiant (YSG). Generally, we expect the progenitors of normal SNe II-P to be red supergiants (RSGs), since the optical P Cygni spectral line profiles and especially the plateau phase of the light curve (arising from a hydrogen recombination wave in the envelope) require such extensive hydrogen envelopes. As discussed in § 2, however, SN 2004et does not have the typical P Cygni profiles, especially for the strong Hα line.
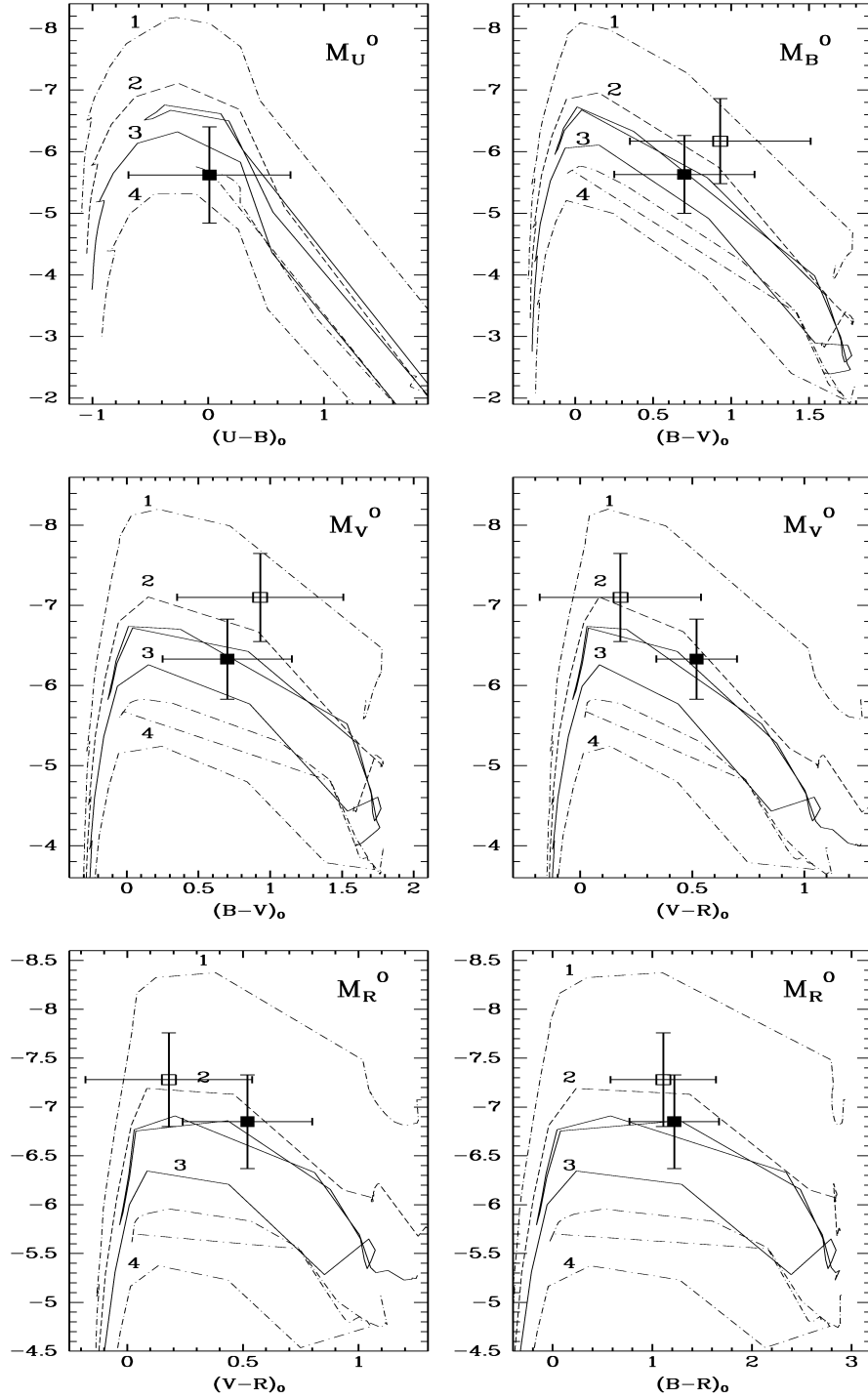
Fig. 7.—Color-magnitude diagrams for the progenitor of SN 2004et. The label for the absolute magnitude along the ordinate is inside each panel. The open square represents the data derived from the *BVR* images, and the filled square represents the Sloan *u′g′r′* image data. Also shown are model stellar evolution tracks for a range of masses from Lejeune & Schaerer (2001), with enhanced mass loss for the most massive stars and solar metallicity ($Z = 0.02$). The tracks labeled 1 to 4 are for $M_{ZAMS} = 20$, 15, 12, and 9 $M_{\odot}$, respectively.
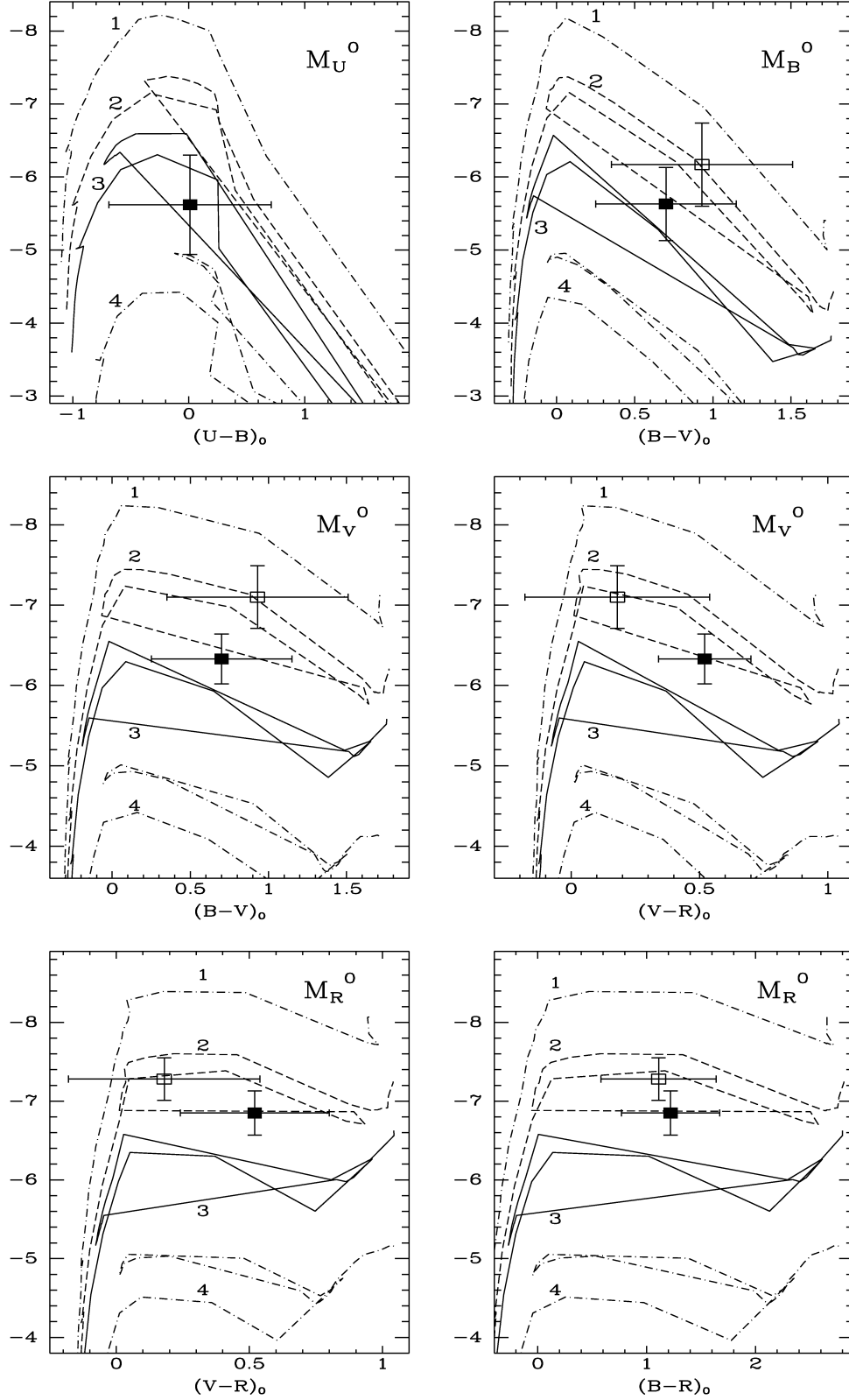
Fig. 8.—Same as Fig. 7, but for a subsolar metallicity, $Z = 0.008$. The tracks labeled 1 to 4 are for $M_{ZAMS} = 20, 15, 12$, and 7 $M_\odot$, respectively.

The estimates for the mass of the progenitor ($M_{\rm ZAMS}$) derived by eye from the CMDs are listed in Table 7. The upper limit with the notation "?" means that the value is uncertain. The median value for each metallicity is also listed. For $Z = 0.02$, we note that the mass estimated from the 2002 image data set (median $= 16^{+6}_{-4}\ M_\odot$) is systematically larger than that from the 2003 data set (median $= 13^{+4}_{-2}\ M_\odot$), although the estimates overlap within the errors. When subsolar metallicity ($Z = 0.008$) is assumed, the mass estimate from the 2002 data set decreases by 1 $M_\odot$ (median $= 15^{+6}_{-2}\ M_\odot$), while the mass estimate from the 2003 data set increases by 1 $M_\odot$ (median $= 14 \pm 2\ M_\odot$), resulting in two estimates that are more consistent with each other. When all mass estimates are considered, the median value is $M_{\rm ZAMS} = 15^{+5}_{-2}\ M_\odot$.

This mass estimate for the progenitor argues against its identification as a compact star cluster, since its mass would have to be several orders of magnitude larger (Maíz-Apellániz et al. 2004). However, we cannot rule out that the object is composed of several stars or is a binary system. One possible scenario is that the object is a RSG and a blue supergiant (BSG) pair, possibly interacting (as may have been the case for the SN 1993J progenitor; e.g., Van Dyk et al. 2002; Maund et al. 2004), and whose combined color is yellow. Our absolute magnitude estimates could be as high as ~0.5 mag brighter than a single supergiant star. In fact, if $M_V^0 \approx -7$ mag and the initial mass range is ~13–20 $M_\odot$ for the SN 2004et progenitor, this is consistent with what Van Dyk et al. (2002) found for the Type IIb SN 1993J, although no indications exist that SN 2004et is of Type IIb.

Furthermore, as seen in both Figures 7 and 8, some massive single stars are expected to evolve between the BSG and RSG phase more than once during their lives, especially at lower metallicities. Theoretically, it is possible that the progenitor evolved off the main sequence, to the BSG phase, and to a YSG phase, before explosion. Alternatively, after evolving from the BSG to a RSG phase, it exploded as a YSG on its way back to the BSG phase. Finally, the star may have evolved from being a BSG to a RSG, then back to the BSG phase, then to a YSG, when it exploded. Such evolutionary "loops" from BSG to RSG to BSG evolution have been invoked to explain the blue progenitor of SN 1987A in the LMC (see Arnett et al. 1989; however, see also Podsiadlowski et al. 1993).

One important discriminator among these various evolutionary scenarios is the amount of circumstellar material (CSM) around the progenitor, expelled as a stellar wind, at the time of explosion. If the progenitor spent any appreciable time as a RSG before explosion, dense CSM might be expected. Radio emission detected from SN 2004et on October 5 (Stockdale et al. 2004), just 14 days after explosion, suggests the presence of appreciable CSM around SN 2004et, so it is quite possible that the progenitor had experienced a RSG stage close to the time of explosion. Further modeling of both the optical and radio properties of SN 2004et is clearly required.

It is also possible that the SN 2004et progenitor is indeed a

TABLE 7
MASS ESTIMATES FOR THE SN 2004et PROGENITOR

CMD	Z	$M_{\rm ZAMS}$ (2002 Data Set)[a]	$M_{\rm ZAMS}$ (2003 Data Set)[b]
$[M_U^0, (U-B)_0]$ ……	0.020	…	$10 + 8 - 2$
$[M_B^0, (B-V)_0]$ ……	0.020	$17 + 6 - 5$	$12 + 6 - 3$
$[M_V^0, (B-V)_0]$ ……	0.020	$17 + 6 - 5$	$12 + 3 - 2$
$[M_V^0, (V-R)_0]$ ……	0.020	$16 + ? - 4$	$13 + 4 - 2$
$[M_R^0, (V-R)_0]$ ……	0.020	$16 + ? - 4$	$13 + 4 - 2$
$[M_R^0, (B-R)_0]$ ……	0.020	$16 + 2 - 3$	$13 + 2 - 2$
Median ……….	0.020	$16 + 6 - 4$	$13 + 4 - 2$
$[M_U^0, (U-B)_0]$ ……	0.008	…	$12 + 4 - 5$
$[M_B^0, (B-V)_0]$ ……	0.008	$16 + 6 - 4$	$14 + 4 - 4$
$[M_V^0, (B-V)_0]$ ……	0.008	$16 + 5 - 3$	$14 + 2 - 2$
$[M_V^0, (V-R)_0]$ ……	0.008	$15 + ? - 2$	$14 + 2 - 2$
$[M_R^0, (V-R)_0]$ ……	0.008	$15 + ? - 2$	$14 + 2 - 1$
$[M_R^0, (B-R)_0]$ ……	0.008	$15 + 2 - 2$	$14 + 2 - 1$
Median ……….	0.008	$15 + 6 - 2$	$14 + 2 - 2$

[a] The $M_{\rm ZAMS}$ estimate from the 2002 image data set (BVR images). The mass is expressed as $M_1 + M_2 - M_3$, where M_1 is the estimated $M_{\rm ZAMS}$, M_2 is the upper limit, and M_3 is the lower limit.

[b] The $M_{\rm ZAMS}$ estimate from the 2003 image data set ($u'g'r'$ images).

RSG, correctly identified in the R and r' images, but that the star we identified in the bluer bands is another, neighboring object (or the RSG is heavily contaminated by other sources). It is also possible that the SN 2004et progenitor has not been detected in the CFHT images and that the object we have identified has no direct connection at all to the SN. Unfortunately, the quality of the CFHT images, although high, is not sufficient to eliminate either of these possibilities. High spatial resolution images of the SN 2004et environment, if obtained with the *Hubble Space Telescope* or with ground-based adaptive optics systems when the SN has significantly dimmed, could provide us with more definitive answers regarding the various possibilities. In addition, high spatial and spectral resolution observations of a sufficiently dimmed SN might reveal the presence of a binary companion, as appears to be the case for SN 1993J (Maund et al. 2004).

5. CONCLUSIONS

Spectroscopic and photometric observations of SN 2004et in NGC 6946 show that it is of Type II. Although the SN exhibits a plateau phase in its light curves, noticeable differences exist in its spectral and color evolution when compared to more normal SNe II-P.

By analyzing the CFHT images of the SN site taken before explosion, we have identified a candidate SN progenitor. The progenitor star appears to be a yellow supergiant with an estimated ZAMS mass of $15^{+5}_{-2}\ M_\odot$, and it may have experienced a red supergiant stage prior to explosion. It is also possible that the progenitor was an interacting binary system

consisting of a red and blue supergiant, similar to the SN 1993J progenitor (Van Dyk et al. 2002). If this star is indeed the SN progenitor, it is only the seventh such progenitor ever directly identified. The mass estimate for the SN 2004et progenitor is consistent with the limits on the progenitor masses for three other SNe II-P: SN 1999gi ($\lesssim 15^{+5}_{-3} M_\odot$; Leonard et al. 2002a), SN 1999em ($\lesssim 20 \pm 5 M_\odot$; Leonard et al. 2003), and SN 2001du ($\lesssim 13^{+7}_{-4} M_\odot$; Van Dyk et al. 2003c). However, it is somewhat higher than the derived progenitor mass for SN 2003gd ($\sim$8–9 $M_\odot$; Van Dyk et al. 2003c; Smartt et al. 2004).

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