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ON THE PROGENITOR OF SN 2005gl AND THE NATURE OF TYPE IIn SUPERNOVAE

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ABSTRACT

We present a study of the Type IIn supernova (SN) 2005gl, in the relatively nearby ($d \approx 66$ Mpc) galaxy NGC 266. Photometry and spectroscopy of the SN indicate that it is a typical member of its class. Pre-explosion *Hubble Space Telescope* (*HST*) imaging of the location of the SN, along with a precise localization of this event using the laser guide star assisted adaptive optics (LGS-AO) system at Keck Observatory, are combined to identify a luminous ($M_V = -10.3$ mag) point source as the possible progenitor of SN 2005gl. If the source is indeed a single star, it was likely a member of the class of luminous blue variable stars (LBVs). This finding leads us to consider the possible general association of SNe IIn with LBV progenitors; it is indeed supported by observations of other SNe, and the known properties of LBV stars. For example, we argue that should the prototypical Galactic LBV η Carina explode in a phase similar to its current state, it will likely produce a SN IIn. We discuss our findings in the context of current ideas about the evolution of massive stars and review the census of SNe with identified progenitors. The concept of the progenitor-SN map is introduced as a convenient means to discuss the present status and future prospects of direct searches for SN progenitors. We conclude that this field has matured considerably in recent years, and the transition from anecdotal information about rare single events to robust associations of progenitor classes with specific SN types has already begun.

Subject headings: instrumentation: adaptive optics — supernovae: general — supernovae: individual (SN 2005gl)

Online material: color figure

1. INTRODUCTION

It is generally assumed that supernovae (SNe) can be divided into two physical classes. Type Ia SNe are assumed to result from the thermonuclear explosion of a degenerate white dwarf star, reaching the critical ignition density as it approaches the Chandrasekhar limit by accretion from, or merger with, a binary companion. Direct observational evidence shows that all other types of SNe result from the gravitational core collapse of young, massive stars. These progenitors are expected to be relatively luminous, and are thus potentially detectable in images of sufficient spatial resolution and depth obtained before these core-collapse SNe explode.

The impact of the study of SN progenitors was vividly illustrated by the watershed case of SN 1987A and its blue supergiant progenitor (White & Malin 1987). Initial surprise at the color (blue rather than red) and compactness of this progenitor led to revisions in our understanding of massive star evolution and SN explosion physics. During the next 15 years progress was slow, with but a single additional progenitor identified (SN 1993J; Aldering et al. 1994; Van Dyk et al. 2002; Maund et al. 2004). Pioneering work by Van Dyk and collaborators (Barth et al. 1996; Van Dyk et al. 1999, 2003a) utilized a new resource—the sensitivity and resolution afforded by pre-explosion images obtained by the *Hubble Space Telescope* (*HST*). Several possible progenitors have been identified, but these associations

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were often inconclusive due to the SN astrometry being limited by postexplosion ground-based images of relatively poor quality.

In the last few years, breakthrough results were presented by two groups (the California group, e.g., Van Dyk et al. 2002, 2003b; Li et al. 2006; and the UK group, e.g., Smartt et al. 2004; Hendry et al. 2006) using mostly postexplosion *HST* imaging to precisely determine the location of SNe and securely identify progenitor stars in pre-explosion *HST* images.

Most recently, we have introduced the use of laser guide star assisted adaptive optics (LGS-AO) as an alternative means for precise SN localization that is independent of *HST* scheduling and operations, and not subject to saturation by the brightness of a young SN (Gal-Yam et al. 2005a, 2005b). Here, we report the second result from our program at the Keck Observatory, the discovery of a luminous point source in pre-explosion images of the Type IIn SN 2005gl.

The paper layout is as follows. In § 2 we present our observations, including analysis of archival pre-explosion *HST* images of the location of this event and our Keck LGS-AO postexplosion observations leading to precise localization of the SN on the pre-explosion grid. In § 3 we present the discovery of a point source consistent with being a very luminous LBV-type progenitor of this SN. We conclude in § 4 with a discussion of our result in the context of accumulated information about SNe IIn and all available SN progenitor identifications to date.

2. OBSERVATIONS

2.1. *Discovery and Photometry*

SN 2005gl was discovered on 2005 October 5.18 (UT dates are used throughout this paper) by Puckett & Ceravolo, and independently by Sano (Puckett et al. 2005). We identified this event as a Type IIn SN (Blanc et al. 2005; § 2.4) using a spectrum obtained with the SNIFS spectrograph mounted on the UH 2.2 m telescope (Fig. 2) on 2005 October 13.5. Pre-explosion imaging (Puckett et al. 2005) places the explosion date of this SN between 2005 September 10 and 2005 October 5.

Unfortunately, the photometric coverage of this event is quite poor, and a light curve in any standard filter cannot be derived from the data currently available to us. However, we are able to extract the light curve of this object from unfiltered survey images of the host galaxy, routinely obtained by the 0.76 m Katzman Automatic Imaging Telescope (KAIT; Li et al. 2000; Filippenko et al. 2001; Filippenko 2005) at Lick Observatory. We use the image-subtraction-based photometry methods of Gal-Yam et al. (2004b) to remove the underlying host-galaxy light and measure the luminosity of this event. The unfiltered light curve has been placed on an *R*-band-equivalent zero point, anchored to four nearby stars for which we obtained photometric calibration with the robotic 1.5 m telescope at Palomar Observatory on 2006 July 26 (Cenko et al. 2006; see Appendix). We find that SN 2005gl peaked at $R \approx 17$ mag around 2006 October 20. Figure 1 shows a comparison between our light curve and those of SN 2004dh, a typical SN II-P (Nugent et al. 2006; A. Gal-Yam et al. 2007, in preparation) and SN 2004ex, a linearly declining SN IIb (A. Gal-Yam et al. 2007, in preparation). As is often seen in SNe IIn, the light curve of SN 2005gl does not show a long plateau phase similar to those of SNe II-P, but it does decline quite slowly for ~50 days, compared to other linearly declining events (SNe II-L/IIb). This slow decline is often attributed to emission contributed by ongoing circumstellar shocks.

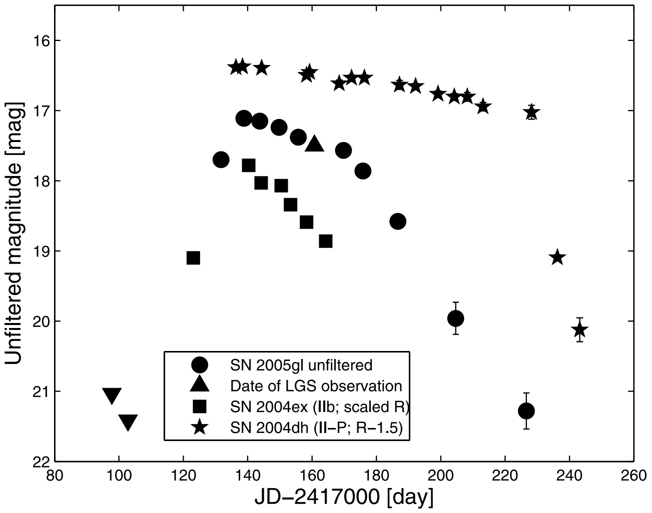

Fig. 1.—Comparison of the scaled unfiltered KAIT light curve of SN 2005gl (*blue circles*) with those of two SNe studied by the CCCP (Gal-Yam et al. 2004a; A. Gal-Yam et al. 2007, in preparation). SN 2004dh is a typical SN II-P, displaying the characteristic long plateau in its *R*-band light curve (*magenta stars*; Nugent et al. 2006; Gal-Yam et al. 2007, in preparation), while the *R*-band light curve of SN 2004ex (*red squares*; Gal-Yam et al. 2007, in preparation) shows a rapid linear decline, typical for SNe IIb and II-L. The light curve of SN 2005gl is intermediate, as is often seen for SNe IIn. A possible interpretation is that the light curve represents the combination of a rapidly declining "linear" component, similar to those observed in other partially stripped SNe of Types IIb and II-L, augmented by an additional contribution from long-lasting circumstellar shocks, which cause the light curve to decline more slowly. The light curves were aligned to have approximately the same peak date, and were arbitrarily scaled for clarity. Error bars are typically smaller than the symbol size, and upper limits are denoted by inverted triangles. [*See the electronic edition of the Journal for a color version of this figure.*]

2.2. *Spectroscopy*

Shortly after its discovery, on 2005 October 13.5, we observed SN2005gl with the SuperNova Integral Field Spectrograph (SNIFS), a high-throughput dual-channel lenslet-based instrument (on the University of Hawaii 2.2 m telescope on Mauna Kea) optimized for automated observation of point sources on a diffuse background (Aldering et al. 2002). The single 1000 s exposure was obtained close to zenith (air mass 1.1), and covers a fully filled $6'' \times 6''$ field-of-view in the 3300–10000 Å extended optical domain with a moderate spectral resolution of 2.5 Å (3300–5100 Å) and 3.4 Å (5100–10000 Å).

The IFS data set was calibrated using a dedicated procedure including CCD preprocessing, diffuse-light subtraction, three-dimensional (3D) data set reconstruction (the extraction procedure uses an optical model of the instrument to locate each of the spectra, and extracts them using optimal weighting, taking account of the flux overlap between adjacent spectra), wavelength calibration, and spectrospatial flat-fielding using internal calibration frames, cosmic-ray removal, and telluric-feature correction.

The flux solution was computed from a spectrum of the white dwarf GD71 acquired for 600 s on the same night at equivalent air mass, using the standard Mauna Kea extinction curve (Beland et al. 1988). The night was reasonably photometric according to CFHT/Skyprobe,[4] with a stable seeing of 1″ FWHM intensity.

The point-source spectra were extracted from the 3D data sets using an aperture-based algorithm (with an aperture radius of 4 and 5 σ for SN 2005gl and GD71, respectively) after uniform background subtraction (estimated outside the aperture). While the supernova lies on a slightly structured host-galaxy background (~1% rms), we estimate the overall accuracy of the SN spectrum flux solution to be ~5% everywhere except at the wavelength domain edges. Based on a preliminary version of this spectrum

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[4] See http://www.cfht.hawaii.edu/Instruments/Elixir/skyprobe/home.html.

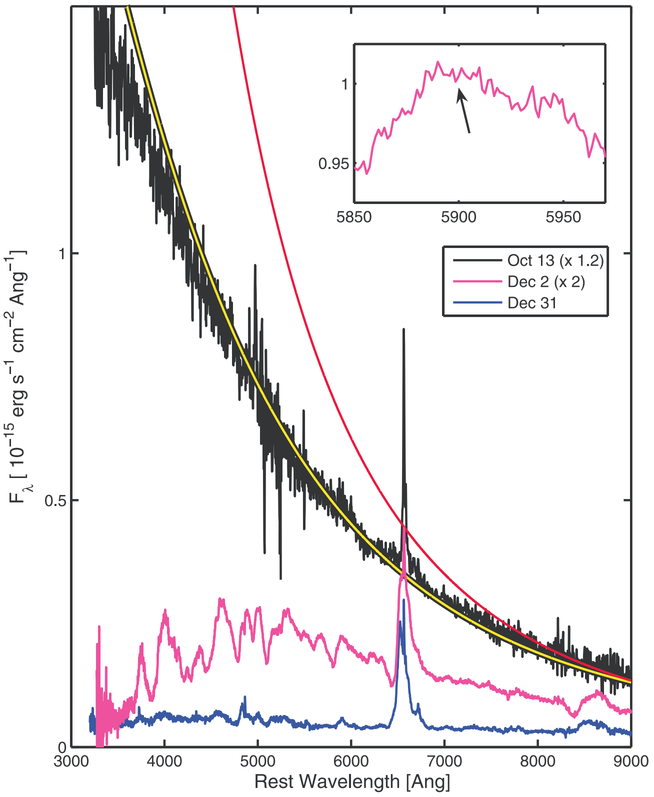

FIG. 2.—Spectra of SN 2005gl. The spectra show strong Balmer Hα and Hβ lines, with a narrow core ($v \approx 400$ km s^{-1}) superposed on a broad base ($v \approx 2000$ km s^{-1}), the hallmark of SNe IIn. Our spectra do not resemble those of the recently discovered hybrid Ia/IIn events such as SN 2002ic (Hamuy et al. 2003; Wood-Vasey et al. 2004) and SN 2005gj (Prieto et al. 2005; Aldering et al. 2006). In particular, they show narrow Fe II lines (typical in spectra of SNe II) in the early December spectrum, and He I lines in emission (5876, 6671, and 7065 Å) in the later one. They markedly lack the prominent, broad Si and Fe line blends observed in SNe Ia and their hybrid SN IIn cousins (see, e.g., Deng et al. 2004; Wang et al. 2004). The inset shows a detailed view of the area around the wavelength of the Na I D line in our highest S/N spectrum (December 2). A weak notch is detected at the correct wavelength (marked), but it is also consistent with being a noise feature. We adopt the strength of this possible feature as an upper limit on the equivalent width of any real Na D absorption, and use this to constrain the extinction toward this SN to be below $A_V = 0.35$ mag. A robust (but less constraining, $A_V < 1.05$ mag) limit is obtained using blackbody fitting to our earliest spectrum (*yellow and red curves*), see § 3.2 for details.

the SN was initially identified as a Type IIn event (Fig. 2; Blanc et al. 2005).

We obtained further spectra of SN 2005gl on 2005 December 2.3 and 31.3 with the Low-Resolution Imaging Spectrometer (Oke et al. 1995) in polarimetry mode (LRISp) on December 31 at the Cassegrain focus of the Keck I 10 m telescope. We used the dichroic filters D55 (D68) to split the spectrum at 5500 Å (6800 Å) on December 2.3 (31.3), respectively, and send the blue and red light to the respective arms of LRIS, where the choice of gratings/grisms yielded a resolution on both sides of ~10 Å and spectral coverage of about 3300–9100 Å. The total exposure times were 1800 s (600 s) on December 2.3 (31.3), and the object was observed at the parallactic angle (Filippenko 1982).

To derive the total-flux spectrum, we extracted the one-dimensional sky-subtracted spectra optimally (Horne 1986) in the usual manner. The spectra were then wavelength and flux calibrated, corrected for continuum atmospheric extinction and telluric absorption bands (Wade & Horne 1988; Bessell 1999; Matheson et al. 2000), and combined. Note that, although we observed with LRISp on December 31.3, SN 2005gl was only observed with a single wave-plate position, and thus polarization information is not available.

The spectral evolution of this object is presented in Figure 2. The earliest SNIFS spectrum is very blue, and well fitted by a blackbody (BB) spectrum with $T = 13{,}000$ K (*yellow curve*). Assuming a very hot intrinsic (unreddened) spectrum (BB with $T = 5 \times 10^5$ K; *red curve*), we find that any dust reddening cannot be stronger than $E_{B-V} = 0.3$ mag ($A_V = 1.05$ mag) without the resulting model spectrum (reddened BB) underpredicting the blue flux. $A_V = 1.05$ mag therefore represents a robust upper limit on the amount of possible dust extinction toward this object (see below).

By December 2, the spectrum has evolved and is now dominated by Balmer and Ca lines with P Cygni profiles and prominent Fe II absorption lines near 5000 Å typical of SNe II at this age (~50 days after explosion). We note that not all SNe IIn show such an evolved absorption spectrum. The last spectrum (December 31) is dominated by emission lines of H and He, while absorption features are weak or have disappeared.

2.3. *Pre-explosion Hubble Space Telescope Observations*

The host galaxy of SN 2005gl, NGC 266, was observed by *HST* in 1997 as part of a program to study nearby galaxies with active nuclei (GO 6837; PI: Ho). Images were obtained in the UV (F218W; data archive designation `u3mj0101m` and `u3mj0102m`, 900 s each)[5] and V (F547M; `u3mj0103m` and `u3mj0104m`, 200 and 160 s, respectively) bands using the Wide-Field and Planetary Camera 2 (WFPC2) instrument. While the galaxy nucleus (the target) was positioned on the PC chip, the location of SN 2005gl was fortunately placed on wide-field chip 2 (WF2). Following the explosion of SN 2005gl in 2005 October, we have located and retrieved these data from the *HST* archive.

The frames were preprocessed through the standard Space Telescope Science Institute (STScI) pipeline using the latest calibrations as of 2005 December 24. The images were further processed using the suite of programs designed specifically for the reduction of WFPC2 data that are available as part of the HSTphot (Dolphin 2000) software package (ver. 1.1.5b; our implementation includes all updates through 2003 May 28), following the procedure outlined by Leonard et al. (2003). When possible, `hstphot` returns magnitudes in standard Johnson-Cousins photometric bands as output. For our observations, the complete transformation to standard V is not possible since color information is not available (i.e., I-band observations were not taken); however, comparison of the flight-system magnitudes with standard V for a different data set (see below) reveals that the color correction is generally under 0.03 mag for most objects, so that our flight-system magnitude should be quite close to the standard V magnitude.

We ran `hstphot` with option flag 14, which combines turning on local sky determination, turning off empirically determined aperture corrections (using default values instead), and turning off point-spread function (PSF) residual determination; these are the recommended settings for a galaxy well beyond the Local Group. By turning off empirical aperture corrections, default values for each filter are applied to the photometry, and are accurate, in general, to 0.02 mag. Hstphot was run with a signal-to-noise ratio (S/N) threshold of 1.0. We identify several point sources near the location of the SN on WF chip 2 (Fig. 3 and Table 1).

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[5] The F218W data were reduced, and no sources are detected down to an instrumental magnitude of ~22.6 mag. Given possible line-of-sight extinction (see below), no useful limit could be drawn on the F218W − F547M color of sources detected in F547M images, so we do not further discuss these data.

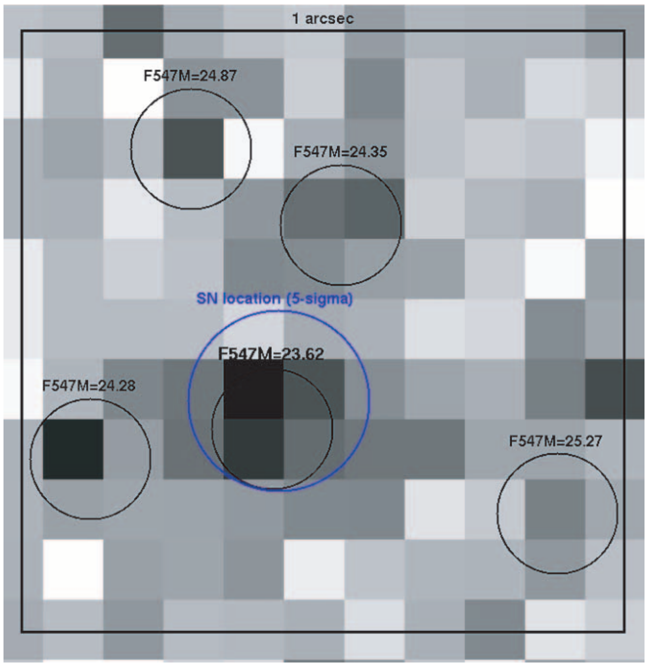

Fig. 3.— Sources near the location of SN 2005gl as seen in pre-explosion *HST* imaging. In black we mark the location and apparent magnitudes of the five point sources identified by HSTphot (§ 2.1 and Table 1). In blue we plot the 5 σ error circle around the location of the SN, as determined from registration of high-resolution postexplosion Keck-AO images onto the pre-explosion *HST* grid (see § 3.1 and Fig. 4). A single point source is consistent with being the progenitor of SN 2005gl. The *HST* image section shown in approximately 1″ on the side; north is up, and east is to the left.

Photometry produced by HSTphot has been compared with that generated by other packages, including DoPHOT (Schechter 1993) and DAOPHOT/ALLFRAME (Stetson 1987, 1994), and the results show excellent agreement (Dolphin 2000). This is not surprising, since most of the machinery of HSTphot, including the star-finding and PSF-fitting algorithms, are in fact modeled after these older packages. The primary advantage of HSTphot is that it has built-in knowledge of WFPC2 instrumental characteristics and hence runs with far less user interaction and produces robust results that are easily reproducible by different users.

However, as far as we are aware, no direct comparisons exist in the literature between HSTphot and other photometry packages for WFPC2 observations using the F547M filter. As a "sanity check" on our implementation of HSTphot, then, we reduced and analyzed the archival *HST* WFPC2 data acquired for the Small Magellanic Cloud as part of a stellar populations study (program GO-8196) using the F547M and F814W filters (data sets `u5ct0201r`, `u5ct0202r`, `u5ct0203r`, `u5ct020dr`, `u5ct020er`, and `u5ct020fr`). A comparison between our `hstphot` *V* and *I* magnitudes with the values derived by McCumber et al. (2005) using the IRAF task APPHOT.PHOT for a sample of stars listed in Table 8 of McCumber et al. (2005) yields excellent overall agreement (the mean offset among the stars checked in 0.06[0.02] mag in *V*[*I*]), building confidence in the robustness of our results.

2.4. *Keck Laser Guide Star Assisted Adaptive Optics Observations*

We observed SN 2005gl on 2005 November 11 with the wide-field channel (plate scale 0.04″ pixel^{-1}) of the Near Infrared Camera 2 (NIRC2) operated behind the laser guide star assisted adaptive optics system (LGSAO; Wizinowich et al. 2006) on the Keck II 10 m telescope on Mauna Kea, Hawaii. At that time (~20 days after peak, Fig. 1) we estimate the brightness of the SN was $K \approx 16 \pm 0.2$ mag in the near-IR (see Appendix for calibration details) and $R \approx 17.5$ mag in the optical (Fig. 1). We observed for 25 × 30 s in a 5 point box dither pattern through the K_p (2.1 μm) filter; the mean epoch of our observations was 07:40 UT.

Calibration products included bias images, afternoon dome flats taken both with and without dome-lamp illumination (to enable subtraction of the underlying thermal signature) and a bad-pixel map, initially derived from the flat fields and then refined during subsequent analysis. After bias-subtraction and flat-fielding, the sky background of individual science frames was estimated and used as a normalization for the purpose of calculating a single fringe image. Note that the domination of the sky background at near-IR wavelengths by bright emission lines inevitably produces fringes. Since fringes are an additive background, it is not strictly appropriate to derive flat fields from night-sky images in the near-IR.

Fringe subtraction was followed by image registration (shift and add), cosmic-ray identification, refinement of the bad-pixel mask, cosmic-ray and bad-pixel masking, and image combination ("`imcombine`") managed using custom software within the Pyraf environment. The resulting co-added image has a FWHM of 0.10″ (2.6 pixels), with a peak signal of 8000 counts from SN 2005gl, which is well below detector and analog-to-digital converter (ADC, 32 bit) saturation. The overall cosmetic quality of the image is not ideal, mainly because diffuse emission from the host galaxy NGC 266 was incorporated into the fringe image, causing misestimation of the sky background in individual frames, with this effect exacerbated by the simple dither pattern. However, these defects are not expected to impact the astrometric utility of the image, and were judged to be sufficiently negligible within the region of interest that a more refined analysis of the data was not attempted.

3. RESULTS

3.1. *A Possible Luminous Progenitor for SN 2005gl*

We have registered the postexplosion Keck-LGS images to pre-explosion *HST* images following the procedures described

TABLE 1

Point Sources near the Location of SN 2005gl

Number	Chip Position (*x*, *y*)	S/N	Counts	Magnitude (Flight System)	Uncertainty (mag)
1	(56.72, 157.95)	7.2	36.401	24.036	0.150
2	(53.67, 157.22)	4.8	21.295	24.607	0.226
3	(58.03, 161.12)	4.3	19.427	24.702	0.255
4	(55.47, 162.42)	2.4	12.922	25.133	0.455
5	(61.63, 156.34)	3.0	12.198	25.195	0.357

Note.— The *x* and *y* positions reported by HSTphot follow the convention that an integer value is assigned to a star that is centered in the lower-left corner of a pixel; this is similar to the output from DoPHOT, but 0.5 lower in both *x* and *y* than in the output from DAOPHOT.

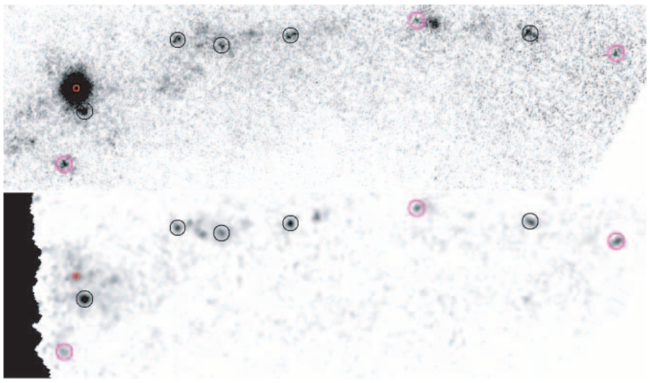

FIG. 4.—Registration of the postexplosion K_p-band Keck-LGS image (*top panel*) onto the pre-explosion *V*-band *HST* image (*bottom panel*). Eight common nearby compact sources are identified and outlined. The three sources marked in magenta were excluded from the final fits (see text). The SN location is determined from the unsaturated Keck image using centroiding algorithms within IRAF, and projected onto the pre-explosion *HST* grid using the geometric solution. The red circle marks the 5 σ error circle, with the uncertainty accounting for both the estimated centroiding and registration errors.

by Gal-Yam et al. (2005a). Briefly, the process included the identification of nearby compact sources (marked in Fig. 4), detected in both images, which are used to calculate the geometric registration solution using the task `geomap` within IRAF. The final solution we obtained had an rms residual of ~0.33 pixel in *x* and 0.36 pixel in *y*, using the five stars circled in black in Figure 4. In magenta we mark three additional sources that match well but were excluded from the final fit due to being too faint in one of the images, or elongated with mismatched centers. Registration using various subsets of the black and magenta sources yielded consistent results. The small overlap area between the *HST* and Keck-LGS images, and small number of available common sources, does not require or justify high-order geometric solutions, so we have solved only for a shift and scale correction between the distortion-corrected *HST* and Keck-LGS frames.

The blue circle in Figure 3 shows the 5 σ error circle (with radius ~0.06″) around the localization of SN 2005gl, as derived from the *HST*-LGS registration demonstrated in Figure 4. The SN location was determined using the centroiding algorithm within IRAF. The centroiding error was estimated by comparing centroid positions obtained using different algorithms and extraction apertures around the SN location, and found to be negligible compared to the uncertainty introduced by the geometric solution. The final uncertainty reported above and presented in Figure 4 was calculated by adding the centroiding and registration uncertainty in quadrature.

A single point source is consistent with the SN location. We measure a flight-system magnitude of 24.04 ± 0.15 for this object (statistical error only). Although we are unable to make a formal color correction to translate this flight-system magnitude into standard *V*, we believe this value is within 0.03 mag of the *V* magnitude (§ 2.1). Adding a conservative value of 0.05 mag to the Poisson uncertainty yields a final, *V*-band magnitude of 24.04 ± 0.16 mag.

Since the host is relatively distant ($z = 0.015547 \pm 0.000017$; Huchra et al. 1999, via NED[6]) we use Hubble's law to calculate a distance of 66 ± 4 Mpc (for $H_0 = 70$ km s^{-1} Mpc^{-1}) to this galaxy, where the error is dominated by the effects of our adopted peculiar velocity uncertainty, $v = \pm 300$ km s^{-1}. The distance modulus is $\mu = 34.1 \pm 0.15$ and thus the absolute magnitude of the putative progenitor is $M_V = -10.3 \pm 0.2$, where we also account for $A_V = 0.23$ mag of Galactic extinction, as derived from the Schlegel et al. (1998) dust maps. If this is a single star, it most likely belongs to the class of luminous blue variables (LBVs, with bolometric absolute magnitudes brighter than $M = -9.5$), to which belong all known stars of such high luminosities, including all the well-studied cases in our Galaxy (see below). Red supergiants (RSGs; $M > -9$ mag),[7] blue supergiants (BSGs; e.g., the progenitor of SN 1987A, $M \approx -8$ mag), and even the so-called rare "cool hypergiants" ($M > -10$ mag) are all fainter than this source (see, e.g., Humphreys & Davidson 1994; their Fig. 9).

3.2. *Caveats and Future Prospects*

The magnitude given above is not corrected for possible extinction in NGC 266, the host galaxy of SN 2005gl. Since objects near the SN location are detected only in a single band in the pre-explosion image, they do not constrain the amount of extinction close to this line of sight. However, the spectroscopy of the SN itself indicates that this value is small. Our data do not show strong Na D absorption lines (Fig. 2, inset), which are correlated with dust extinction (see Turatto et al. 2003 for the latest compilation). The notch seen at the location of the Na D line in our spectrum is consistent with a noise feature. Adopting its strength as an upper limit on any real Na D absorption, the measured equivalent width (EW = 0.03 Å) implies $E_{B-V} = 0$ mag using the latest formulas from Turatto et al. (2003). As can be seen in Figure 3 of that work, all SNe with Na D lines weaker than EW = 0.2 Å have measured $E_{B-V} \lesssim 0.1$ mag, which we therefore adopt as a conservative upper limit on dust extinction along this line of sight, implying $A_V <$ 0.35 mag.

In addition, the very blue spectrum of the SN at early time argues against significant extinction. We follow Leonard et al. (2002) in quantifying this observation as follows. Figure 2 shows that the early spectrum of SN 2005gl is well fitted by a blackbody spectrum with $T = 13{,}000$ K (*yellow curve*). Also plotted is the blackbody curve for a source with $T = 500{,}000$ K, representing the hottest intrinsic spectrum one can suggest for a SN a few days after explosion (*red curve*). Reddening this putative hot spectrum using the Cardelli et al. (1989) law with $R = 3.08$ and extinction values of $E_{B-V} > 0.3$ mag results in model observed spectra that are redder (underpredict the blue flux) than our SNIFS spectrum. We therefore conclude that $E_{B-V} = 0.3$ mag ($A_V \approx 1.05$ mag) is a robust upper limit on the optical extinction of SN 2005gl (the likely value, as argued above, is much smaller). Note that such modest host extinction would increase the implied luminosity of the putative progenitor star, making an LBV identification even stronger.

The main caveat in establishing that the point source we have detected in the pre-explosion *HST* imaging is the progenitor of SN 2005gl is the possibility that this source is a compact, luminous star cluster, rather than a single star. Compact luminous clusters with properties similar to those we measure (often called "super star clusters," or SSCs) are observed in starburst or interacting galaxies. However, they are generally rare in more normal galaxies (with but a single SSC candidate, Westerlund 1, observed in our Galaxy) and are expected to be even less frequent in

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[6] See http://nedwww.ipac.caltech.edu.

[7] Massey & Olsen (2003) have recently identified very luminous red supergiants in the LMC with bolometric luminosities $M > -10$ mag. However, due to their large bolometric corrections (*V*-band luminosities below $M_V = -7$), these cannot account for the source we discuss here.

earlier type galaxies such as NGC 266 (an Sa galaxy; Nilson 1973, via NED). The majority of massive SN progenitors in early spirals are not found in SSCs, and thus we believe that SN 2005gl probably did not explode in such an environment. However, this possibility cannot be ruled out at this time. Additional *HST* imaging obtained once SN 2005gl declines should provide decisive evidence, with the point source at the SN location either gone (if it was a single star) or remaining approximately at the same magnitude, if it is indeed an SSC.

Additional support for the association between SNe IIn (such as SN 2005gl) and LBV progenitors could arise if additional such cases are discovered. While SNe IIn are intrinsically rare (Cappellaro et al. 1997), they tend to be overrepresented in observed SN samples due to their high average luminosity. In addition, the luminosity of LBV progenitors makes them visible in galaxies that are far more distant than hosts of less luminous stars. The number of such galaxies in the *HST* archive is higher than the number of nearby ones ($d < 20$ Mpc) usually considered as likely candidates for progenitor studies, again increasing the opportunity to test the association of SNe IIn with LBV progenitors in the future.

4. DISCUSSION AND CONCLUSIONS

4.1. *SNe IIn from LBVs*

We now examine the hypothesis that LBV stars explode as SNe IIn. The class of SNe IIn is known to be a heterogeneous group of events. At least two subsets represent specific and probably unrelated phenomena to the one we consider here, namely, the core-collapse-driven explosion of a massive LBV star, similar, for example, to the well-known η Carina in our Galaxy. The first unrelated class is that of the so-called SN impostors, believed to be superoutbursts of LBVs that do not result in total disruption of the progenitor star (see, e.g., Van Dyk 2005 and Maund et al. 2006 and references therein). These events are typically faint (compared to a normal SN) with absolute magnitudes between -10 and -14 (Van Dyk 2005), while "genuine" Type IIn explosions (Schlegel 1990) are much brighter (sometime reaching $M = -20$ mag; SN 2005gl has $M \approx -17$ mag). The second group of events which are also probably irrelevant to our discussion are the recently discovered class of "hybrid" SNe Ia/IIn, including the prototype SN 2002ic (Hamuy et al. 2003; Wood-Vasey et al. 2004) along with its recent (SN 2005gj [Prieto et al. 2005; Aldering et al. 2006]) and past (SN 1997cy [Germany et al. 2000; Turrato et al. 2000] and SN 1999E [Filippenko 2000; Rigon et al. 2003]) clones (Hamuy et al. 2003; Deng et al. 2004; Wang et al. 2004). These SNe display spectral properties similar to those of thermonuclear SNe Ia, along with narrow Balmer lines that probably result from strong interaction with circumstellar material in the immediate vicinity of the exploding star. Such events have been suggested to be thermonuclear SNe Ia, exploding either in close proximity to recently stripped gas from a binary companion with intense mass loss (e.g., an asymptotic giant branch star; Hamuy et al. 2003) or within a symbiotic system. Another possibility is that they are thermonuclear explosions that occur while the envelope of the exploding star is still intact ("SNe 1.5"; Iben & Renzini 1983). In any case, SN 2005gl does not share the spectroscopic properties of these hybrid events, and does not appear to be related to this SN IIn subclass (Fig. 2). We note that both of the subgroups discussed above comprise a minority within the observed population of SNe IIn.

So, we can reformulate our question as follows: Can LBVs be the progenitors of most SN IIn explosions? We focus on the best-studied example of an LBV in our Galaxy, η Carina. The envelope of this star still contains large quantities of hydrogen (e.g., Davidson et al. 1986), so, had it exploded now, it would result in a Type II (H-rich) SN. In addition, we observe the results of copious mass loss around this system, of order several solar masses of ejected material, mostly H. Were an energetic explosion to occur at the center of such a huge debris cloud, we would expect strong interaction leading to strong narrow H lines—the hallmark of SNe IIn. Thus, we conclude that an LBV exploding during the active mass-ejection phase, or shortly thereafter, would indeed appear to distant observers as a SN IIn.

The rates of SNe IIn may shed some light on our proposed progenitor association. Let us consider a simplistic massive-star evolutionary scheme, for *single* stars with approximately solar metallicity, broadly following, e.g., Maeder & Conti (1994). We use the customary notations RSG for red supergiants, WN for N-rich (and usually also He-rich) Wolf-Rayet stars, WC for C-rich W-R stars, and WO for O-rich W-R stars.

$$80\ M_\odot < M < 150\ M_\odot\text{:}\ \ \mathrm{O} \rightarrow \mathrm{LBV} \rightarrow \mathrm{SN\ IIn(?)}, \quad (1)$$

$$40 M_\odot < M < 80 M_\odot\text{:}\ \mathrm{O} \rightarrow \mathrm{LBV} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC/WO} \rightarrow \mathrm{SN\ Ic}, \quad (2)$$

$$25\ M_\odot < M < 40\ M_\odot\text{:}\ \ \mathrm{O} \rightarrow \mathrm{LBV} \rightarrow \mathrm{(early)WN} \rightarrow \mathrm{SN\ Ib}, \quad (3)$$

$$15 M_\odot < M < 25 M_\odot\text{:}\ \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{(late)WN} \rightarrow \mathrm{SN\ II - L/IIb}, \quad (4)$$

$$8\ M_\odot < M < 15\ M_\odot\text{:}\ \ \mathrm{B/O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{SN\ II - P}. \quad (5)$$

We note that SNe IIn can, in this picture, occur in two distinct cases. First, it is believed that massive stars undergo short LBV phases, involving rapid and strong mass loss. These episodes transform H-rich supergiants to W-R stars, and occur also during early W-R evolution stages (while the stars still have significant amounts of H, i.e., are WN stars; see, e.g., Maeder & Conti 1994). Since the evolution of the inner core is decoupled from that of the envelope during these stages, in some cases the core might collapse during such a short-lived transition phase, resulting in SNe IIn from stars in a mass range comparable to that of the progenitors of SNe IIb/L and Ib/c. In this context we note the recent work by Chugai & Chevalier (2006) interpreting the observations of SN 2001em, which exploded as a SN Ic, and then developed strong interaction signatures (a bright radio signal accompanied by SN IIn-like narrow Hα lines; Stockdale et al. 2004; Soderberg et al. 2004; Bietenholz & Bartel 2005). Models by these authors suggest that SN 2001em underwent a violent and intense, hydrogen-rich, mass-ejection episode, shortly ($\lesssim$1000 yr) before the SN explosion. It appears that SN 2001em exploded shortly after it exited a recent LBV phase, and had a similar event occurred slightly (on stellar evolution timescales) earlier, it would have appeared as a SN IIn.

The second case is a speculative option, which we now describe. We hypothesize that in the case of the most massive stars (eq. [1]) the evolution of the core might be rapid enough to overtake the progress of envelope mass loss, and that these stars might undergo core collapse while in their first LBV phase, before they are significantly stripped. SNe IIn in this case take the place of SNe Ic as the end products of the rare, most massive stars. It is interesting to note in this context that explosion models of SNe Ic,

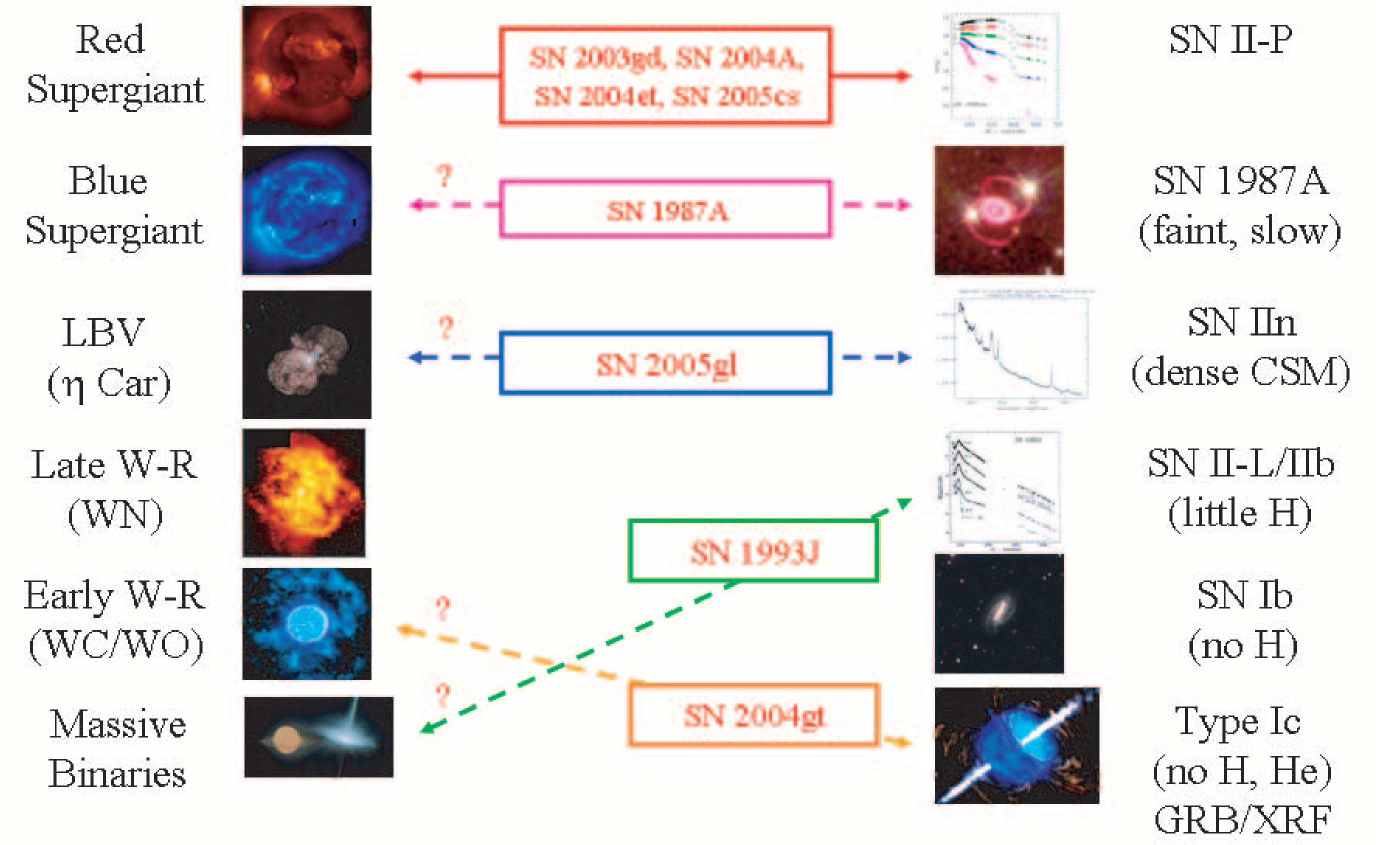

FIG. 5.—Progenitor-SN map, presenting associations of SNe with progenitor stars based on direct observations of the progenitors in pre-explosion images. The association of the most common type of core-collapse events, SNe II-P, with (relatively) low-mass (8 $M_\odot < M < 15$ $M_\odot$) red supergiants (RSGs), appears to be quite robust. The connections between fainter SN II events (1987A–like) and the Type IIn subclass, with blue supergiants and LBVs, respectively, is but suggestive, based on a single event in each case. The progenitors of stripped-envelope events (Type Ib/c) are yet to be observed, but analysis of available upper limits suggests that the progenitors of the more highly stripped (Type Ic) SNe are more evolved (and less luminous) "early" W-R stars, while SNe Ib, which still retain much of their He envelope, result from somewhat less evolved (and often more luminous) "late" W-R stars. Data used are from White & Malin (1987), Aldering et al. (1994), Van Dyk et al. (2002, 2003b), Maund et al. (2004, 2005b), Smartt et al. (2004), Li et al. (2005), Maund et al. (2005a), Li et al. (2006), Hendry et al. (2006), Gal-Yam et al. (2005a), and this work.

including the most energetic ones associated with GRBs (e.g., Deng et al. 2005; Mazzali et al. 2006), require massive progenitors (with zero-age mass $\lesssim 50$ $M_\odot$), but not as massive as the claimed masses of the most extreme LBVs (>80 $M_\odot$), e.g., η Carina (Figer et al. 1998), LBV 1806 (Eikenberry et al. 2004), or the Pistol star (Figer et al. 1998). This scenario, in which the core evolution overtakes the envelope stripping, is not in accord with current stellar evolution models. Still, we think it is an interesting option that merits further theoretical and observational examination.

We note that Chugai et al. (2004) interpret their observations of the Type IIn SN 1994W as indicating that the progenitor underwent an explosive mass ejection shortly before its core collapsed and led to its final explosion as a SN. This would fit well with the above picture of SNe IIn resulting from LBVs like η Carina (which are known to undergo extreme and violent mass-loss episodes) during or shortly after their active phase.

In either of the above cases, we expect these SNe from LBV progenitors to be rare (either because LBVs are short-lived phases, or because the progenitors are very rare stars). For example, the total number of stars with initial mass above 80 $M_\odot$ is $\sim$3% of the total core-collapse progenitor population (8 $M_\odot < M <$ 150 $M_\odot$) for a Salpeter (1955) initial mass function. This is similar to the estimated fraction of SNe IIn of the total core-collapse population ($\sim$2%, Cappellaro et al. 1997). We conclude that the notion that some or most SNe IIn result from explosions of LBVs appears broadly consistent with available observational data.

4.2. *SN 2005gl in Context: The SN-Progenitor Map*

In Figure 5 we summarize the accumulated knowledge from direct observations of SN progenitor stars in the form of a "progenitor-SN map." As possible progenitor classes we consider red and blue supergiants (RSGs and BSGs), LBVs, early (He rich) and late (C/O rich) Wolf-Rayet (W-R) stars, and massive binaries. On the SN side we list all the major well-defined subclasses of core-collapse SNe. Among the H-rich Type II subclasses, SNe II-P have extended (plateau) optical light curves, while SN 1987A-like events are fainter and have a late hump-like peak in their optical light curves. SNe IIn (excluding the specific subsets described in § 4.1 above) generally have blue and rather featureless spectra together with Balmer emission-line profiles which include a narrow component (<1000 km s^{-1}). Moreover, they are often very luminous in the optical, consistent with a strong contribution from shocked circumstellar material. The transition class of SNe II-L/IIb have rapidly declining light curves and often display strong He lines, developing into events with spectra similar to those of SNe Ib (see below). Of the H-poor SNe I, Type Ib events are dominated by He lines, while Type Ic events lack both H and He and are dominated by intermediate-mass elements such as O, Mg, Si, and Ca; see Filippenko (1997) for a general review of SN spectra. Spectra of the optical transients associated with nearby long gamma-ray bursts (GRBs) and X-ray flashes (XRFs) have shown signatures typical to SNe Ic of the broad-lined variety (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Malesani et al. 2004; Soderberg et al. 2005). It is likely that a small fraction of SNe Ic give rise to such high-energy explosions (Soderberg et al. 2006b; Gal-Yam et al. 2006). It must be stressed that this is, by necessity, a simplified presentation of the core-collapse SN ''zoo,'' and that many peculiar objects that do not strictly fit into this picture, or transition objects that are either intermediate or evolve between classes, are known. Still, this scheme should include the majority of observed objects.

We suggest that the progenitor-SN map is a useful tool with which to present and discuss this topic. Of course, we have no guarantees that this map is complete (perhaps more progenitor classes or SN types are required), or that it is a one-to-one mapping. Most likely this version will evolve in the future, but let us use it for the time being as a basis for discussion. We note that the association of SNe II-P with low-mass RSG progenitors is well-supported by four observed events, with no known counterexamples, and maintain that this association is now progressing from suggestive to robust (including also numerous supporting upper limits; Smartt et al. 2006). Studies of the (H- and He-poor) Type Ic SN 2004gt (Gal-Yam et al. 2005a; Maund et al. 2005b) and to a lesser degree SN 2002ap (Smartt et al. 2002) suggest these had highly evolved (i.e., optically less luminous) W-R progenitors, perhaps of the WC or WO subclasses. This may fit well with the population of less evolved W-R stars (late WN) exploding as He-rich Type Ib events, consistent with recent explosion models by Tominaga et al. (2005). This picture is consistent with that expected from stellar evolution theory. The case of the transition class of SNe IIb (which evolve from having H-dominated Type II spectra toward the He-dominated Type Ib class) is less clear. Observations of the prototypical event SN 1993J in M81 (e.g., Filippenko et al. 1993, 1994) suggest a possible massive binary progenitor (Aldering et al. 1994; Van Dyk et al. 2002; Smartt et al. 2004), with some support from the recent work on SN 2001ig (Ryder et al. 2004, 2006). However, it has not been proved that the nearby putative companion stars were indeed physically important or even bound to the SN progenitors. Also, perhaps some SNe IIb arise from single WN (H rich) W-R stars (Soderberg et al. 2006a).

Finally, we note that SNe IIn, which show evidence for intense interaction with circumstellar material suggesting heavy recent mass loss from the progenitor, appear to require a different progenitor from those so far discussed. Red supergiants have little recent mass loss, and so had the blue supergiant progenitor of SN 1987A. While LBVs are not the only option, they provide an elegant solution, as discussed above. It would appear that our putative map now encompasses all main SN types. Of course, more data are required to establish a robust mapping, and we would like each line to be supported by several progenitor-SN associations (as is the case for SNe II-P and red supergiants). Additional cases may also lead to an understanding of the effects of other parameters (beyond initial mass) such as metallicity, rotation, and binarity.

4.3. *Conclusions*

We have identified a luminous point source in pre-explosion images of the location of the Type IIn SN 2005gl. If this was a single star, it was most likely an LBV, based on luminosity considerations. We have discussed a major caveat—the possibility that this pointlike source is actually a compact luminous cluster—and ways by which this progenitor identification can be tested by future observations. We suggest that an association of SNe IIn with LBV progenitors accommodates much of what is currently known about both LBVs and SNe IIn.

We introduce the progenitor-SN map and use it as a basis to discuss our finding. This field has rapidly progressed in recent years and should evolve from a collection of isolated fragmented pieces of information to become based on more solid concepts (such as the progenitor-SN map). These should soon begin to provide useful constraints on models, and drive additional progress in understanding the last stages of massive star evolution and the physics of SNe.

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APPENDIX A

APPENDIX: PHOTOMETRIC CALIBRATIONS

We calibrated the field of SN 2005gl in *VR* using observations of Landolt (1992) standard fields (PG 1657+078, PG 0231+051, and SA 95) obtained with the robotic 1.5 m telescope at Palomar Observatory (Cenko et al. 2006) on the night of 2006 July 25. The IRAF procedure `meastan` by D. Maoz was used to calculate photometric solutions, which are well behaved, indicating that the night was

TABLE 2

Calibration Stars near SN 2005gl

Star Number	R.A. (J2000.0)	Decl. (J2000.0)	V (mag)	R (mag)
1	00 49 57.24	+32 18 53.1	15.57	15.36
2	00 49 52.45	+32 18 43.4	16.51	16.39
3	00 49 43.61	+32 19 01.0	14.40	14.26
4	00 49 43.74	+32 18 48.0	14.76	15.02
5	00 49 44.32	+32 18 10.0	15.43	15.23
6	00 49 36.00	+32 18 01.6	17.02	17.06
7	00 49 40.69	+32 14 20.7	16.53	16.75
8	00 49 59.84	+32 14 23.0	15.81	15.64
9	00 49 59.21	+32 16 57.4	17.56	18.44

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

probably photometric. The overall zero-point calibration uncertainty is ~5%. Table 2 and Figure 6 report the locations and magnitudes of stars near the SN location.

The following equations were used to calculate the calibrated magnitudes:

$$R = -2.5 \times \log(\text{counts s}^{-1}) + 22.112 - \text{air mass} \times 0.136 - (V - R) \times 0.065, \tag{A1}$$

$$V = -2.5 \times \log(\text{counts s}^{-1}) + 21.952 - \text{air mass} \times 0.222 + (V - R) \times 0.023. \tag{A2}$$

We calibrated the K_p-band magnitude of SN 2005gl in our NIRC2 LGS image by bootstrap calibration, based on two common objects detected in the deep and narrow NIRC2 image and in a wider, more shallow K_s-band image of the area obtained with the Wide-Field Infrared Camera (WIRC; Wilson et al. 2003) mounted on the 5 m Hale Telescope at Palomar Observatory on 2006 July 20. The WIRC image was reduced using the CCCP IR pipeline, in a manner similar to that described above for the NIRC2 data, and calibrated against the 2MASS catalog using the methods described by Gal-Yam et al. (2005a).

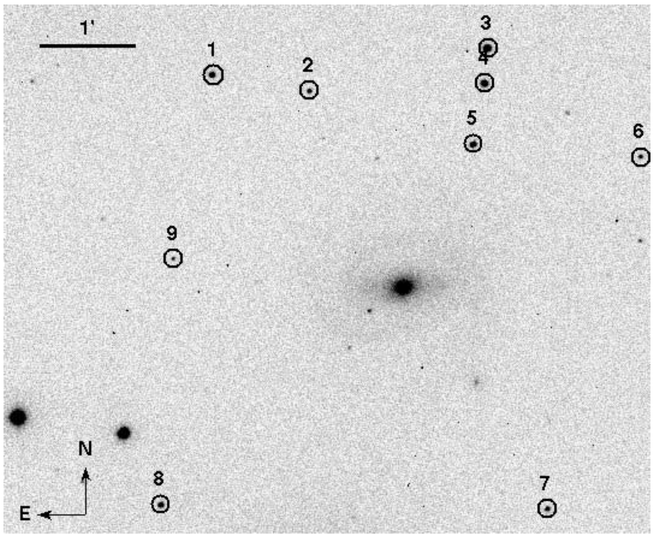

Fig. 6.—Field calibration. Nine stars close to the host galaxy of SN 2005gl (NGC 266), with magnitudes listed in Table 2, are circled. Only stars 2, 5, 6, and 7 appeared in the smaller KAIT field of view and were used to derive the light curve of SN 2005gl.

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