A Search for Core-Collapse Supernova Progenitors in Hubble Space Telescope Images

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ABSTRACT. Identifying the massive progenitor stars that give rise to core-collapse supernovae (SNe) is one of the main pursuits of supernova and stellar evolution studies. Using ground-based images of recent, nearby SNe obtained primarily with the Katzman Automatic Imaging Telescope, astrometry from the Two Micron All Sky Survey, and archival images from the Hubble Space Telescope, we have attempted the direct identification of the progenitors of 16 Type II and Type Ib/c SNe. We may have identified the progenitors of the Type II SNe 1999br in NGC 4900, 1999ev in NGC 4274, and 2001du in NGC 1365 as supergiant stars with $M_V \approx -6$ mag in all three cases. We may have also identified the progenitors of the Type Ib SNe 2001B in IC 391 and 2001is in NGC 1961 as very luminous supergiants with $M_V \approx -9$ mag, and possibly the progenitor of the Type Ic SN 1999bu in NGC 3786 as a supergiant with $M_V \approx -8$ mag. Additionally, we have recovered at late times SN 1999dn in NGC 7714, 2000C in NGC 2415, and 2000ew in NGC 3810, although none of these had detectable progenitors on pre-supernova images. In fact, for the remaining SNe only limits can be placed on the absolute magnitude and color (when available) of the progenitor. The detected Type II progenitors and limits are consistent with red supergiants as progenitor stars, although possibly not as red as we had expected. Our results for the Type Ib/c SNe do not strongly constrain either Wolf-Rayet stars or massive interacting binary systems as progenitors.

1. INTRODUCTION

Determining the progenitor stars that give rise to supernovae (SNe) is at the heart of SN research and is certainly a key aspect of stellar evolution studies. Without knowledge of the nature of SN progenitors, many of the conclusions and inferences that have been made from SNe on the chemical evolution of galaxies, the energy input into the interstellar medium, the production of stellar remnants such as neutron stars and black holes, the origin of cosmic rays, and even the determination of cosmological distances stand on precarious ground. The main obstacle is that an SN leaves few traces of the star that exploded. Additionally, only a small handful of the more than 2000 historical SNe have had pre-explosion objects identified. These include SN 1961V in NGC 1058 (Zwicky 1964, 1965), SN 1978K in NGC 1313 (Ryder et al. 1993), SN 1987A in the LMC (e.g., Gilmozzi et al. 1987; Sonneborn, Altner, & Kirshner 1987), SN 1993J in M81 (Aldering, Humphreys, & Richmond 1994; Cohen, Darling, & Porter 1995), and SN 1997bs in M66 (Van Dyk et al. 1999a, 2000). It should be noted that these five SNe were all at least somewhat unusual, and both SN 1961V (Goodrich et al. 1989; Filippenko et al. 1995; but see also Van Dyk, Filippenko, & Li 2002a) and SN 1997bs (Van Dyk et al. 2000) may not have been actual SNe (defined to be the catastrophic explosion of a star at the end of its life).

SNe are characterized optically by the presence or absence of H in their spectra near maximum brightness: the Type II SNe (SNe II) and Type I SNe (SNe I), respectively. SNe I further divide into SNe Ia, which are characterized by a deep absorption trough around 6150 Å produced by blueshifted Si ii λ6355, and SNe Ib/c, which do not show this trough. SNe Ib exhibit strong He i absorption, while SNe Ic show little or no evidence for He i absorption. The SNe II also include various subtypes: SNe II-plateau (II-P) and II-linear (II-L), based on the shape of their light curves (but with associated spectral characteristics as well; Schlegel 1996; Filippenko 1997), and SNe II-narrow (II-n), which lack the blueshifted component of the broad Balmer-line P Cygni profiles, but instead show a relatively narrow emission component atop the broad one. SNe IIb may be a bridge between the SNe II and Ib/c, possessing...
properties of each. (See Filippenko 1997 for a thorough review of SN spectra and types.)

SNe Ia are thought to arise from the thermonuclear deflagration and/or detonation of a white dwarf; but they are not the focus of this paper. SNe II and Ib/c probably arise from the collapse of the Fe core toward the end of the life of a massive \( (M \approx 10 M_\odot) \) star. Whereas it is generally agreed that SNe II must arise from the explosions of hydrogen-rich supergiant stars, the progenitors of SNe Ib/c have not been unambiguously identified. Clearly, SNe Ib/c must arise from stars that have lost most or all of their hydrogen envelopes. As such, Wolf-Rayet stars have been proposed as possible progenitors (see Branch, Nomoto, & Filippenko 1991 and references therein). Alternatively, Uomoto (1986), Nomoto, Filippenko, & Shigeyama (1990), Polsiaklowski, Joss, & Hsu (1992), Iwamoto et al. (1994), and Nomoto et al. (1996) have explored massive gas-transferring binary systems as possible SN Ib/c progenitors. (Another possibility, now considered much less likely, are off-center explosions of white dwarfs; Branch & Nomoto 1986.)

Part of the evidence for the core-collapse nature of SNe II and Ib/c comes from theoretical modelling (e.g., Woosley & Weaver 1986, 1995), but indications that these SNe have massive-star progenitors also stems from the few that have had progenitors directly identified: for SN 1961V, an extremely luminous \( (M_\nu \approx -12 \text{ mag}) \) star (Bertola 1964; Zwicky 1964; Klemola 1986); for SN II 1978K, a reddish star, with \( B-R \approx 2 \text{ mag} \) and \( M_\nu \approx -6 \text{ mag} \) (Ryder et al. 1993); for SN II-P 1987A, a massive blue supergiant (e.g., Woosley 1988); for SN IIb 1993J, a red supergiant, possibly in a binary system (Podsiadlowski et al. 1993; Aldering et al. 1994; Van Dyk et al. 2002b); and for SN II 1997bs, a supergiant star with \( M_\nu \approx -7.4 \text{ mag} \) (Van Dyk et al. 1999a, 2000). In addition, several young SN remnants, such as Cas A (e.g., Fesen, Becker, & Blair 1987; Fesen & Becker 1991; Garcia-Segura, Langer, & Mac Low 1996), clearly point toward massive progenitors.

Evidence for massive progenitors has also been accrued from the environmental data for many SNe. Van Dyk (1992) and Van Dyk, Hamuy, & Filippenko (1996) provided statistics of the association of SNe II and Ib/c with massive star-formation regions, from ground-based imaging. More recently, Barth et al. (1996) and Van Dyk et al. (1999a, 1999b) have exploited the superior spatial resolution afforded by the Hubble Space Telescope (HST) to resolve individual stars in SN environments and place constraints on the progenitor ages and masses. Based on the properties of the surrounding stellar association, Van Dyk et al. (1999b), in particular, concluded that the progenitor of the SN II-L 1979C in M100 had an initial mass \( M \approx 17-18 M_\odot \).

Using HST images of SN 1993J in M81 to remove contamination by neighboring stars of the ground-based estimates of the progenitor brightness (Aldering et al. 1994), Van Dyk et al. (2002b) constrain the progenitor mass to be \( \sim 13-22 M_\odot \).

Clearly, direct identification of the progenitors of additional core-collapse SNe is essential. Van Dyk et al. (1999a, 2000) were able to directly identify the progenitor star for SN 1997bs using HST archival images. However, at that point in time the quantity of archival data in which pre-SN images might exist for recent SNe was extremely small. We can now reap the benefits from the confluence of two circumstances: the increasing data volume in the HST archive and the success of modern SN searches. In particular, the Lick Observatory SN Search (LOSS; Li et al. 1999; Filippenko et al. 2001) and the Lick Observatory and Tenagra Observatory SN Searches (LOTSS; Schwartz et al. 2000; Beutler et al. 2002), with which two of us (W. D. L. & A. V. F.) are involved and which are discovering new SNe at a remarkable rate (e.g., 65 in 2002 January–September).

In this paper, we discuss our attempt to isolate the progenitors of 16 core-collapse SNe (six SNe II and 10 SNe Ib/c) using HST Wide Field Planetary Camera 2 (WFPC2) images of galaxies. It will only be through the accumulation of a statistically significant number of direct identifications of progenitor stars for both SNe Ib/c and SNe II that we finally will be able to adequately test the various models for massive stellar evolution and inevitable explosion.

2. METHOD OF ANALYSIS

We began by cross-referencing historical SNe with the HST archive. We compiled a list of core-collapse events, all since about 1997 through 2002 June, which might contain the progenitor star in at least one WFPC2 image. A summary of the available data is in Table 1. The crux of this work is determining at which location on the four chips of the image array the star should be. It is therefore of utmost importance to have high astrometric accuracy for all the images. Ideally, one could pinpoint the exact SN location by comparing a late-time image of the SN with a pre-SN image. In fact, in three cases below, we have been able to do this. However, even locating the fading SN in HST images is often quite difficult and requires high astrometric precision.

It is reasonably straightforward to measure accurate positions (to fractions of an arcsecond) for SNe on high-quality ground-based images. However, it is well known that positions based on the astrometric information in the HST image headers alone are not very accurate. Online documentation\(^2\) for WFPC2 claims an accuracy of \( \sim 0.5 \) arcsec from experience, however, we have found it to be more typically \( \sim 1.5 \) or worse (see, e.g., Filippenko et al. 1995; Van Dyk et al. 1999a). It is thus incumbent upon us to apply an independent astrometric grid to the WFPC2 images.

For this reason we have adopted the Two Micron All Sky Survey (2MASS) as the basis for the astrometric grid for both the ground-based SN images and the HST images potentially containing the SN progenitor. While it is well known that the 2MASS near-infrared catalogs are an unprecedented photo-

\(^2\) http://www.stsci.edu/instruments/wfpc2/Wfpc2_faq/wfpc2_ast_faq.html.
### TABLE 1

Summary of Available Data

| SN        | Host Galaxy | Date (UT) | Filters | Exposure Time (s) | HST Program |
|-----------|-------------|-----------|---------|------------------|-------------|
| 1998Y ..... | NGC 2415    | 1997 May 19 | F547M   | 700              | GO-6862     |
|           |             |           | F656N   | 600              |             |
|           |             |           | F814W   | 560              |             |
|           |             | 2001 Mar 11 | F555W   | 700              | GO-8602*    |
|           |             | 2002 May 3 | F300W   | 600              | GO-9124     |
| 1999an ..... | IC 755      | 1995 Jan 5 | F606W   | 160              | GO-5446     |
| 1999br ..... | NGC 4900    | 1995 Jan 29 | F606W   | 160              | GO-5446     |
|           |             | 2002 Jun 20 | F450W   | 460              | GO-9042     |
|           |             |           | F814W   | 460              |             |
| 1999bu ..... | NGC 3786    | 1995 Mar 30 | F606W   | 500              | GO-5479     |
| 1999bx ..... | NGC 6745    | 1997 Mar 19, 21 | F336W | 22000           | GO-6276     |
|           |             |           | F555W   | 4800             |             |
|           |             |           | F675W   | 5200             |             |
|           |             |           | F814W   | 5200             |             |
| 1999dn ..... | NGC 7714    | 1996 May 15 | F606W   | 500              | GO-5479     |
|           |             | 1998 Aug 29 | F380W   | 1800             | GO-6672     |
|           |             | 2001 Jan 24 | F814W   | 700              | GO-8602*    |
|           |             | 2001 Jul 10 | F555W   | 700              |             |
|           |             | 2001 Aug 3 | F300W   | 300              | GO-9124     |
| 1999ee ..... | NGC 2207    | 1996 May 25 | F336W   | 2000             | GO-6483     |
|           |             |           | F439W   | 2000             |             |
|           |             |           | F555W   | 660              |             |
|           |             |           | F439W   | 720              |             |
| 1999ev ..... | NGC 4274    | 1995 Feb 5 | F555W   | 280              | GO-5741     |
| 2000C .....  | NGC 2415    | 1997 May 19 | F547M   | 700              | GO-6862     |
|           |             |           | F656N   | 600              |             |
|           |             |           | F814W   | 560              |             |
|           |             | 2001 Mar 11 | F555W   | 700              | GO-8602*    |
|           |             | 2002 May 3 | F300W   | 600              | GO-9124     |
| 2000ds ..... | NGC 2768    | 1999 May 20 | F555W   | 400              | GO-6587     |
|           |             |           | F814W   | 2000             |             |
| 2000ew ..... | NGC 3810    | 1994 Nov 4 | F606W   | 160              | GO-5446     |
|           |             | 2001 Nov 7, 8 | F450W | 460              | GO-9042     |
|           |             |           | F814W   | 460              |             |
| 2001B .....  | IC 391      | 1994 Feb 21 | F555W   | 70              | GO-5104     |
| 2001ai ..... | NGC 5278    | 2000 Dec 18 | F255W   | 1400             | GO-8645     |
|           |             |           | F300W   | 1500             |             |
|           |             |           | F814W   | 260              |             |
| 2001ci ..... | NGC 3079    | 1999 Mar 4 | F547M   | 320              | GO-7278     |
|           |             |           | F814W   | 140              |             |
|           |             | 2001 Jan 21 | F606W   | 560              | GO-8597     |
|           |             | 2001 Dec 9 | F300W   | 800              | GO-9124     |
| 2001du ..... | NGC 1365    | 1995 Jan 15 | F336W   | 100              | GTO-5222    |
|           |             |           | F555W   | 100              |             |
|           |             |           | F814W   | 100              |             |
| 2001is ..... | NGC 1961    | 1994 Aug 28 | F218W   | 1800             | GO-5419     |
|           |             |           | F547M   | 300              |             |
|           |             | 2001 Jul 14 | F547M   | 4000             | GO-9106     |
|           |             |           | FR680N  | 4000             |             |

* This is part of our own Snapshot program (PI: Filippenko); see Li et al. 2002.
metric resource, a less recognized fact is that the Point Source Catalog is also of outstanding astrometric quality, with residuals in the final Catalog typically and conservatively \(0.10\) (H. McCallon & R. Cutri 2002, private communication). The J-band 2MASS images correspond quite well with the optical SN and \(HST\) images, such that a sufficient number of astrometric fiducial stars on the optical images can be employed to achieve accuracies in the astrometric solutions of typically \(0.2\)–\(0.3\). For WFPC2 this means, with a plate scale of \(0.1\) pixel \(^{-1}\), that we can estimate the position of the progenitor star on a WF chip with uncertainty in the range of only 3–9 pixels (roughly double this pixel range for the PC chip).

Unless otherwise specified, we have measured all of the SN positions from \(R\)-band or unfiltered images obtained by the Katzman Automatic Imaging Telescope (KAIT; Filippenko et al. 2001; KAIT is the principal instrument for LOSS/LOTROSS), as part of KAIT SN light-curve monitoring (see, e.g., Li et al. 2001; Modjaz et al. 2001a; Leonard et al. 2002a, 2002b). We then use the STSDAS routine \texttt{wmosaic} within IRAF\(^3\) to stitch together the four WFPC2 chips to obtain the full WFPC2 field of view. (This step is generally necessary for there to be enough available fiducial stars to facilitate the astrometry.) The \texttt{wmosaic} routine makes corrections for geometric distortion in each chip and for the rotation, offsets, and scale differences among the chips. Application of 2MASS to the full mosaic results in an astrometric reference frame, or grid, of satisfactorily high accuracy, verified by the resulting positions of at least one or more “check stars” on the mosaic. (The key, again, is that we are not employing the \textit{HST} image header information, but imposing our own astrometric grid on the mosaic.)

Often we could match unsaturated stars on the WFPC2 mosaic with 2MASS sources and directly derive an astrometric solution for the mosaic. When this was not possible, owing to a lack of 2MASS sources seen on the WFPC2 mosaic, we matched 2MASS sources first with relatively bright (but unsaturated) stars on deep optical images (typically \(V\) band) of the SN host galaxies (obtained in 2002 February and April at the Palomar 1.5 m telescope) and then, once an astrometric solution had been obtained, matched fainter stars seen in both the deep ground-based images and the WFPC2 mosaic, obtaining a new astrometric solution based on these objects. All astrometric solutions were derived throughout using the IRAF task \texttt{ccmap} and applied using \texttt{cctrans}. Finally, we then determined the individual WFPC2 chip pixel value and the uncertainty in that value for the SN site and, therefore, for the progenitor.

Once the site was located, photometry of the appropriate WFPC2 chip was performed using the routine \texttt{HSTphot} (Dolphin 2000a, 2000b), which automatically accounts for WFPC2 point-spread function (PSF) variations and charge-transfer effects across the chips, zero points, aperture corrections, etc., and can return magnitudes in standard Johnson-Cousins bands as output, whenever possible. \texttt{HSTphot} was run in all cases with a \(3\) \(\sigma\) detection threshold. Dolphin (2000a) tested \texttt{HSTphot} against \texttt{DoPHOT} on the same dataset and found no systematic differences in the results from the two packages. Similarly, Saha et al. (2001), in their measurement of the Cepheid distance to NGC 3982, find the \texttt{HSTphot} results to be within the errors of the \texttt{DoPHOT} results. Extensive tests by D. C. Leonard (2002, private communication) of \texttt{DAOPHOT} against \texttt{HSTphot} also show very good agreement (in particular, on images of NGC 3351, he finds \(\delta V = 0.016\) and \(\delta I = 0.043\) mag; see Graham et al. 1997). Consequently, we can determine the magnitude and, when available, the color of the candidate progenitor, although, as we will see, for most objects this turns out to be placing only a \textit{limit} on the magnitude and color.

In three cases we were able to recover the SN in a late-time image, allowing us to isolate the exact position of the progenitor. These detections serve as a valuable test of our method: if the astrometric grid is truly accurate, we should be able to locate the old SN in a straightforward manner, which, in fact, proves to be the case. We emphasize that, short of having an accurate absolute position for these SNe, the generally faint sources would be relatively difficult to unambiguously locate on a WFPC2 chip, especially with the possible presence of other variable stars in the host galaxy. The coincidence of the estimated SN position on the chip with the actual recovery position provides us with some confidence in the progenitor positions for the other cases, where no late-time image of the SN is available.

All quoted positions are J2000.0 throughout. All observing dates are in UT, and the relevant \textit{HST} GO or GTO program is given in each case. Unless otherwise specified, the distance to the host galaxy is derived from the heliocentric radial velocity corrected for Local Group infall into the Virgo Cluster given in the Lyon-Meudon Extragalactic Database (LEDA) and is based on an assumed distance scale of 65 km s\(^{-1}\) Mpc\(^{-1}\). For lack of other data, the extinction correction toward the SN is limited in most cases to the Galactic component (generally adopting \(A_V\) from the NASA/IPAC Extragalactic Database [NED], and originally from Schlegel, Finkbinder, & Davis 1998), assuming the Cardelli, Clayton, & Mathis (1989) reddening law. All limiting magnitudes and colors, unless otherwise specified, are based on the \(3\) \(\sigma\) detection limits. Below we discuss the individual core-collapse SNe and their possible progenitors.

### 3. THE SUPERNOVAE AND THEIR PROGENITORS

#### 3.1. SN 1999an in IC 755

SN 1999an was discovered by Wei et al. (1999) as part of the Beijing Astronomical Observatory (BAO) SN Search and was classified as an SN II by Cao & Gu (1999). We measure...
the SN position from a KAIT image as $\alpha = 12^h01^m10.57^s$, $\delta = +14^\circ06'11.1''$, with uncertainty $\pm 0.4''$. The host galaxy was imaged in F606W (160 s) by GO-5446 on 1995 January 5. The Galactic foreground stars around the host on the WFPC2 mosaic are quite faint, so we used a deep Palomar V-band image to establish the astrometric grid for the mosaic. The uncertainty in the positions for these stars in the Palomar image is $\pm 0.2''$. However, applying the grid to the mosaic resulted in an uncertainty of $\pm 0.6''$, likely due to the relative faintness of the stars in the mosaic. Together with the measured uncertainty in the SN position, this results in a total uncertainty of $\pm 0.8''$ in the SN position on the mosaic (the uncertainties in the measured SN position and in the astrometric grid were added in quadrature here and throughout).

Figure 1 shows the SN site on the WF2 chip. Within the error circle are six objects, with $m_{F606W} \approx 21.9-22.9$ mag. However, HSTphot considers them all to be spatially extended (non-stellar). Assuming a host galaxy distance of 23 Mpc (based on Tully-Fisher estimates by Yasuda, Fukugita, & Okamura 1997) and Galactic $A_V = 0.1$ mag, these objects have $M_V \approx -9.0$ to $-10.0$ mag, which are at the extreme end of observed stellar luminosity in the Milky Way (e.g., Humphreys & Davidson 1979). It is therefore likely that these are compact star clusters. The progenitor may have been a member of one of these clusters, and we are unable to resolve it. It is also possible that the progenitor was not a member and also not detected in the image. If the latter is the case, then from the detection limit in the SN environment ($m_{F606W} \approx 25.0$ mag), we can place an upper limit on the progenitor’s absolute visual magnitude of $M_V \approx -6.9$ mag.

3.2. SN 1999br in NGC 4900

SN 1999br was discovered by King (1999) as part of LOSS and was classified as an SN II by Garnavich et al. (1999a) and Filippenko, Stern, & Reuland (1999); the latter point out that the SN is very subluminous, regardless of its type. Patat et al. (1999) and Zampieri et al. (2002) conclude that a smaller than “normal” $^{56}$Ni mass must have been produced in the explosion. Nonetheless, Hamuy & Pinto (2002) consider SN 1999br as an SN II-P. We measure the SN position from a KAIT image as $\alpha = 13^h00^m41.82^s$, $\delta = +02^\circ29'45.4''$, with uncertainty $\pm 0.2''$. The host galaxy was imaged in F606W (160 s) by GO-5446 on 1995 January 29. The stars useful for astrometry in the WFPC2 mosaic are all quite faint (the bright star near the SN position is saturated); therefore, we used a deep Palomar V-band image to establish the astrometric grid for the mosaic, with uncertainty $\pm 0.3''$, which results in a total uncertainty of $\pm 0.5''$.

Figure 2 shows the SN site on the WF3 chip. A very faint object is seen within the error circle, but it is not detected by HSTphot. A brighter object is detected along the north-north-east edge of the circle, with $m_{F606W} = 24.96 \pm 0.27$ mag. Tentatively, we assign this as the possible progenitor of SN 1999br (it is detected in the F606W image at the 4 σ level). The host galaxy has also been very recently (on 2002 June 20) and more deeply imaged by GO-9042 in F450W and F814W (460 s each). It is therefore possible that we can detect the SN at late times and pinpoint the exact progenitor location. We applied the same grid as on the F606W mosaic to the F450W and F814W mosaics, using four of the same five faint fiducial stars.

Figure 3 illustrates the SN site on the PC chip and also shows that the astrometry produces quite similar results as in Figure 2 for the SN location. However, no object is detected within the error circle to $B \approx 25.3$ and $I \approx 24.5$ mag. This is consistent with an extrapolation from the late-time SN photometry (SN 1999br was last detected in 2000 April at $B \approx 23.6$ and $I \approx 21.2$ mag, and, following the $^{56}$Co decay rate, a decline of $\approx 8$ mag is expected between 2000 April and 2002 June; A. Pastorello 2002, private communication). We therefore most likely have not recovered the SN in these 2002 images. However, the fact that the possible progenitor object identified above is no longer detected in the deep F450W and F814W images indicates that we may have identified the SN progenitor in the older (1995) F606W image.

For a distance of 17.3 Mpc (Ho, Filippenko, & Sargent 1997) and Galactic extinction toward the host galaxy $A_V = 0.08$ mag (Hamuy & Pinto [2002] list $A_V \approx 0$ mag within the host, based on the SN color at the end of the plateau), we find that $M_V \approx -6.3$ mag for this star, consistent with that for late-type (M-type) supergiants (Humphreys & Davidson 1979). Unfor-
Fig. 2.—Site of SN 1999br in NGC 4900 in an archival 160 s F606W image from 1995 January 29. The error circle has radius 0.5. A possible progenitor star, with \( M_V \approx -6.3 \) mag, is identified along the north-northeast edge of the circle and indicated with tick marks.

Unfortunately, no color information exists for this star. If it is not the progenitor, we can place a limit on the progenitor’s absolute magnitude of \( M_V \approx -5.9 \) mag, based on the F606W image detection threshold (\( m_{F606W} \approx 25.4 \) mag).

3.3. SN 1999bu in NGC 3786

SN 1999bu was discovered by Li (1999) using KAIT; about 1" west and 3" south of the host galaxy nucleus. Jha et al. (1999a) classified it as an SN Ic. NGC 3786 was imaged by GO-5479 in a single 500 s F606W exposure on 1995 March 30. Only two stars are seen in the WFPC2 mosaic. For this reason, we performed an offset from a relatively bright (but unsaturated) star 11.96 west and 11.90 north of the SN site. This offset was determined from a KAIT image of the SN, after galaxy background light had been subtracted to make it easier to derive a centroid for the SN. We applied the same offset from this star on the WFPC2 mosaic, and we show the SN position on the PC chip in Figure 4. We have adopted an uncertainty in the offset which is the uncertainty in the astrometry of the KAIT image, namely, ±0.5.

Three objects are detected within and along the northern edge of the error circle. Object A is considered extended by HSTphot and has \( m_{F606W} = 23.62 \pm 0.01 \) mag. Object B is also considered extended and has \( m_{F606W} = 23.54 \pm 0.01 \) mag. Object C, just east of north along the circle edge, is considered stellar and has \( m_{F606W} = 25.72 \pm 0.31 \) mag.

For a distance of about 42 Mpc (correcting the distance of 36.1 Mpc from Pogge & Martini 2002 to our assumed distance scale) and Galactic extinction \( A_V = 0.08 \) mag, objects A and B, presumably small star clusters, have \( M_V \approx -9.6 \) and \( -9.7 \) mag, respectively, brighter than known supergiants. Object C, however, has \( M_V \approx -7.5 \) mag, consistent with supergiant brightnesses; although it is at the edge of the error circle, it could possibly be the progenitor. Alternatively, the progenitor may have been a member of the two clusters and is unresolved. It is also possible that it was not object C, was not a cluster member, and was not detected. If the latter is the case, then from the detection limit in the SN environment (\( m_{F606W} \approx 26.1 \) mag), we estimate \( M_V \approx -7.1 \) mag for the progenitor.

3.4. SN 1999bx in NGC 6745

SN 1999bx was discovered using KAIT by Friedman & Li (1999). The host galaxy, NGC 6745 (UGC 11391), may actually be an interacting galaxy pair, and the SN occurred about 2" west and 15" north of the southern of the two nuclei. Jha et al. (1999c) classified it as an SN II. From a KAIT image, we measure the SN position as \( \alpha = 19^h01^m41.39^{s}, \delta = +40^\circ44'52.7'', \) with uncertainty ±0.2. NGC 6745 was imaged very deeply in F336W (22,000 s), F555W (4800 s), F675W (5200 s), and F814W (5200 s) on 1997 March 19 and 21 by GO-6276. Applying the 2MASS astrometric grid directly to the F555W mosaic, with total positional uncertainty ±0.4, we show in Figure 5 the SN site on the WF3 chip.

We detect four objects (A–D) within, or along the edge of,
the error circle, and with the good color coverage discussed above, we can derive useful information about them. HSTphot considers the two objects at the western circle edge, A and B, to be stellar, with $V_p = 24.37$ and $25.01$ mag, respectively, whereas the two eastern objects, C and D, are likely extended, with $V_p = 23.75$ and $23.53$ mag, respectively. Assuming a distance of about 74 Mpc and Galactic extinction $m_V$, the two western objects, A and B, have $M_p = -9.8$ mag, whereas the two eastern objects, C and D, have $M_p = -11.3$ mag, almost certainly too bright to be single stars. Additionally, objects A and B are quite blue: for A, the reddening-corrected colors are $(U-V)^0 = 0.38$, $(V-R)^0 = 0.19$, and $(R-I)^0 = 0.20$ mag; and, for object B, $(U-V)^0 = -0.56$, $(V-R)^0 = 0.60$, $(R-I)^0 = 0.20$, and $(V-I)^0 = 0.80$ mag. Colors for object B indicate that it may be a composite of blue and red objects.

It is therefore likely that the detected objects are too luminous and too blue to be the possible progenitor of SN 1999bx, since as an SN II, we might expect the progenitor to have been a red supergiant. We cannot rule out that the progenitor was either an unresolved member of likely clusters C and D, or was blended with luminous stellar objects A or B. However, if it is undetected, limits on the absolute magnitude and color of the progenitor are $M_V^p \geq -7.8$, $(U-V)^0 \leq 0.5$, $(V-R)^0 \leq 0.9$, $(R-I)^0 \leq 1.0$, and $(V-I)^0 \leq 1.6$ mag. (Color limits here and throughout are derived from the larger SN environment, ~10" or so, depending on the image, and are not particularly restrictive.)

3.5. SN 1999dn in NGC 7714

SN 1999dn was discovered by Qiu et al. (1999) as part of the BAO SN Search. It was classified as an SN Ic by Ayani et al. (1999) and Turatto et al. (1999). Pastorello et al. (1999) describe the strong resemblance of SN 1999dn to SNe 1997X, 1994I, and 1996aq around maximum brightness, with He i lines detected; they argue that it should be considered as an SN Ib/c. Deng et al. (2000) and Matheson et al. (2001a) further refine the classification to Type Ib; Branch et al. (2002) consider it the currently best-observed, “fiducial” SN Ib. Deng et al. (2000) also find strong evidence for both Hα and C II at 6580. They conclude that the low-mass H skin above the He layer in SN 1999dn makes this event a possible link between SNe Ib and IIb, such as SN 1993J (e.g., Filippenko, Matheson, & Ho 1993). From a KAIT image we measure the SN position as $\alpha = 23^336^14:81$, $\delta = +02^09^08^24$, with uncertainty ± 0.5. SN 1999dn is potentially one of the more interesting objects in this study, since we can attempt to detect the faint SN in one of our own HST Snapshot images (GO-8602; see Li et al. 2002, which does not include SN 1999dn in the analysis) and compare this with the pre-SN archive image. We obtained a 700 s F814W image (cosmic-ray split pair) on 2001 January
Fig. 6.—SN 1999dn in NGC 7714, as seen in our 700 s F814W Snapshot image from 2001 January 24. The SN is most likely the star indicated with tick marks within the 0"/H11033.6 error circle. It had mag. By July 10, the SN had faded below detectability in both the F555W and F814W bands. We have applied the routine qzap to remove residual cosmic-ray hits.

Fig. 7.—Site of SN 1999dn in NGC 7714 in a single archival 500 s F606W exposure from 1996 May 15. We have applied the routine qzap to make the image more cosmetically appealing. The error circle has radius 0"/H11033.6. No star is detected at the exact position of the SN in Fig. 6, indicated with tick marks.

24 and 700 s splits each in F555W and F814W on 2001 July 10. However, this turned out to be one of the most difficult sets of HST images for which to establish an astrometric grid, because of the lack of stars in common between these images and 2MASS detections (unfortunately, we did not observe the host galaxy at Palomar). Nonetheless, we can apply a grid, with ±0.4 uncertainty, and locate the SN on the PC chip for the first pair of F814W exposures from 2001 January, with total uncertainty ±0.6. The SN is most likely the faint object just east of the error circle center in Figure 6 (we have applied the routine qzap, written by M. Dickinson, to the image in the figure to remove residual cosmic-ray hits; the object to the south is seen at about the same brightness in the second F814W image pair from 2001 July). The SN had mag. It is undetected in either band of the second set of Snapshot images, to mag. Galactic extinction is mag. To derive possibly more accurate limits on the brightness and color of a progenitor star, we exploit the color information available to us for objects in the F380W image to . For a distance of about 43 Mpc and Galactic A_v = 0.17 mag (Turatto et al. [1999] indicate no extinction to the SN), the corrected magnitude and color correspond to , (U-V) = 2.50 mag for the progenitor.

3.6. SN 1999ec in NGC 2207

SN 1999ec was discovered using KAIT by Modjaz & Li (1999). The SN was classified as an SN Ib by Jha et al. (1999b), although Matheson et al. (2001a) consider it a peculiar SN I, without a well-defined type, similar to SN 1993R (see Filippenko & Matheson 1993). We measure on a KAIT image the SN position ash16m 16s.18, with uncertainty ±0.2. (This position is discrepant by at least 1" with that referred to by Elmegreen et al. 2001.) The host galaxy is part of an interacting system, extensively studied by Elmegreen et al. with HST (GO-6483); only their “NGC2207-NW” F336W (2000 s), F439W (2000 s), F555W (660 s), and F814W (720 s) images from 1996 May 25 are of use here. We apply the 2MASS astrometric grid directly to the WFPC2 F555W mosaic, with uncertainty ±0.2. Figure 8 shows the SN site on the F555W WF2 chip, with total uncertainty ±0.3.

A hint of an object is possibly seen within the circle, but nothing is detected there by HSTphot to V ≥ 25.9 mag. The Galactic extinction is A_v = 0.29 mag. To derive possibly more accurate limits on the brightness and color of a progenitor star, we exploit the color information available to us for objects in
Fig. 8.—Site of SN 1999ec in NGC 2207 in an archival 660 s F555W image from 1996 May 25. The error circle has radius 0\arcsec. Two objects identified as stellar by HSTphot are indicated with tick marks (see Fig. 9). Star 1, with $M_V \approx -11.2$ mag, is likely too bright to be a single star. The progenitor, therefore, is likely not detected.

Fig. 9.—$(U-B, V-I)$ color-color diagram for the SN 1999ec environment. The two stellar objects indicated in Fig. 8 are represented by open triangles; the extended objects are represented by open squares. The locus of the main sequence is shown, as is the reddening vector, following the Cardelli et al. (1989) reddening law.

the SN’s environment, to possibly estimate the local extinction. As can be seen from the color-color diagram in Figure 9, HSTphot considers most of the objects around the error circle to be extended; they are likely star clusters. However, two objects are considered stellar, and the one (Star 1) closest to the SN position implies that $A_V \approx 1.6$ mag (although the $U$-band photometry may be the least certain, the extinction, even for the clusters, appears to range from ~1 to ~3 mag). Although it is at the edge of the error circle, it is possible that star 1, with $V = 23.42$, $(U-B)^0 = -0.3$, and $(V-I)^0 = -0.8$ mag, is the progenitor. Adjusting the distance to the host from Elmegreen et al. (2001) to about 40 Mpc for our adopted distance scale, and assuming the $A_V$ derived from star 1, this leads to the star having a very blue intrinsic color $[(U-B)^0 = -1.3$, $(B-V)^0 = -0.1$, and $(V-I)^0 = -0.2$ mag], but also $M_V^0 \approx -11.2$ mag, which is likely too high for known stars. If star 1 is not the progenitor, which we consider more likely, then $M_V^0 \approx -8.7$, $(U-B)^0 \leq -0.3$, $(B-V)^0 \leq 0.2$, and $(V-I)^0 \leq 0.9$ mag for the progenitor.

3.7. SN 1999ev in NGC 4274

SN 1999ev was discovered by T. Boles of the U.K. Nova/Supernova Patrol (Hurst 1999) and was classified as an SN II by Garnavich et al. (1999b). We measure from a KAIT image the SN position as $\alpha = 12^h19^m48^s20, \delta = +29\degree37\arcmin21\arcsec7$, with uncertainty ±0\arcsec4. This agrees, to within the errors, with the position measured by Armstrong (1999), but disagrees with the positions measured by Boles and by Garnavich et al. The host galaxy was imaged by GO-5741 in F555W (280 s) on 1995 February 5. We applied the 2MASS grid directly to the WFPC2 mosaic for the four faint stars in common, with uncertainty ±0\arcsec7, leading to a total uncertainty ±0\arcsec8. Figure 10 shows the SN site on the WF2 chip. The two brightest of the faint objects within the error circle, labeled A and B, have $m_F^{555W} = 24.93 \pm 0.2$ and $25.28 \pm 0.3$ F555W mag. Assuming a distance of about 17 Mpc and Galactic $A_V \approx 5.9$ mag, these correspond to $M_V^0 \approx -6.3$ and $-5.9$ mag, respectively. Either of these is consistent with the absolute magnitudes of red supergiants and could be the progenitor. If neither of these two stars is the progenitor, then it had $M_V^0 \approx -5.5$ mag.

3.8. SN 2000C in NGC 2415

SN 2000C was independently discovered by S. Foulkes and M. Migliardi (Foulkes et al. 2000). It was classified as an SN Ic by Cappellaro et al. (2000) and Jha et al. (2000). We measure the SN position from a galaxy background-subtracted KAIT image as $\alpha = 07\degree36\arcmin57\arcsec11, \delta = +35\degree14\arcmin39\arcsec0$, with uncertainty ±0\arcsec2. This position agrees, to within the errors, more with that measured by Migliardi than with that measured originally by Li.

We (GO-8602) obtained a F555W 700 s Snapshot image (in a cosmic-ray split pair) on 2001 March 11. The host galaxy...
Fig. 10.—Site of SN 1999ev in NGC 4274 in an archival 280 s F555W image from 1995 February 5. The error circle has radius 0.8. Two faint objects within the error circle, A and B, with $M_i \approx -6.3$ and $-5.9$ mag, respectively, are indicated with tick marks. Either of the two could be the progenitor of this SN II.

Fig. 11.—Site of SN 2000C in NGC 2415 in a 700 s F555W Snapshot image from 2001 March 11. The error circle has radius 0.5. The SN is almost certainly the star with $m_{F555W} = 22.74$ mag, indicated with tick marks within the circle.

Fig. 12.—Site of SN 2000C in NGC 2415 in an archival 700 s F547M image from 1997 May 19. The error circle has radius 0.5. No star is detected at the exact position of the SN in Fig. 11, indicated with tick marks.

was also imaged by GO-6862 on 1997 May 19 in F547M (700 s), F656N (600 s), and F814W (560 s), and by GO-9124 on 2002 May 3 in F300W (600 s). We applied the 2MASS astrometric grid directly to the unsaturated and partially saturated stars on the F555W mosaic, with a total uncertainty of $\pm 0.5$ in the SN position on the mosaic. Figure 11 shows this position on the PC chip. Within the error circle is a point source with relatively high signal-to-noise ratio (S/N), which is almost certainly the SN at late times, with $m_{F555W} = 22.74 \pm 0.07$ mag. We can be confident of the SN identification, since this object is seen on both of the cosmic-ray splits and is not seen in the pre-SN F547M image of similar depth (Fig. 12) or in the F814W PC images. The SN is not detected on the F300W WF3 chip on 2002 May 3 to $m_{F300W} \geq 22.9$ mag (however, the star cluster to the west of the SN is quite bright in this band). In neither the F547M nor the F814W image is a progenitor candidate detected, to $V \approx 25.1$ and $V-I \approx 1.3$ mag. For a distance of about 60 Mpc and Galactic $A_v = 0.14$ mag, this corresponds to $M_V \approx -8.9$ and $(V-I) \approx 1.2$ mag for a progenitor.

SN 1998Y, which was discovered by Li et al. (1998) using KAIT and classified as an SN II by Filippenko, Leonard, & Riess (1998), also occurred in this host galaxy. Because of poor seeing, the faintness of the SN, and high galactic background in the KAIT images, it is difficult to obtain a good centroid for the SN in order to accurately determine its position. From a relatively crude position and its proximity to SN 2000C...
(within 2º), we know that the SN site is also on the Snapshot image (PC chip). We have very carefully subtracted the light of the pre-SN F547M image from that of the Snapshot image and inspected a circular region with radius 60 pixels centered on the SN 2000C position (60 pixels on the PC chip is ~3º), but we could not locate SN 1998Y. It must have faded below detectability by 2001 March. (It should be noted that the subtraction very nicely reveals SN 2000C.) The limit on the brightness of SN 1998Y in 2001 March is \( V \gtrsim 25.9 \) mag. We did not try to locate the SN 1998Y progenitor in any of the pre-SN images, owing to the crude position.

3.9. SN 2000ds in NGC 2768

SN 2000ds was discovered by Puckett & Dowdle (2000) and classified as a relatively old SN Ib by Filippenko & Chornock (2000). From a KAIT image we measure the SN position as \( \alpha = 09^h11^m36^s28, \delta = +60^\circ01'43''3, \) with uncertainty \( \pm 0'3. \) The host galaxy was imaged by GO-6587 on 1999 May 20 in F555W (1000 s and also 400 s) and in F814W (2000 s). Only two of the stars seen on the 1000 s F555W mosaic have 2MASS counterparts; the rest are too faint. For this reason we established a secondary astrometric grid using a deep Palomar -band image of the host, with uncertainty \( \pm 0'4. \) The resulting grid applied to the WFPC2 mosaic has uncertainty \( \pm 0'5, \) for a total uncertainty of \( \pm 0'7 \) in the SN position on the mosaic. Figure 13 shows the SN site on the WF2 chip. Although hints of faint, reddish clusters of stars may be evident near the SN position at the 3–4 \( \sigma \) level (\( I \approx 25.7–24.7 \) mag), generally no star is detected to \( V \gtrsim 26.6 \) and \( V–I \leq 1.6 \) mag. For a distance of about 25 Mpc and Galactic \( A_V = 0.15 \) mag, this corresponds to \( M_V \approx -5.5 \) and \( (V–I)_0 \approx 1.5 \) mag for the progenitor.

3.10. SN 2000ew in NGC 3810

SN 2000ew was discovered by Puckett & Langoussis (2000) and classified as an SN Ic by Filippenko, Chornock, & Modjaz (2000). From a KAIT image we measure the SN position as \( \alpha = 11^h40^m58^s60, \delta = +11^\circ27'55''8, \) with uncertainty \( \pm 0'3. \) (This position differs by \( \sim 1'' \) or more from those reported by Puckett & Langoussis and by Garradd 2000.) The host galaxy was imaged by GO-9042 in F450W and F814 W (460 s each) on 2001 November 7–8 and by GO-5446 in F606W (160 s) on 1994 November 4. The host is quite large on the mosaics, and the Galactic stars on the F814W mosaic are too faint for 2MASS, so we established an astrometric grid using a deep Palomar \( V \)-band image. Applying this grid to the WFPC2 mosaic, the uncertainty is \( \pm 0'6, \) leading to a total uncertainty of \( \pm 0'7 \) in the SN position on the mosaics.

In Figure 14, we show the SN position on the F814W WF3 chip. Toward the southeast edge of the error circle is a point source, which we identify as the fading SN. Our confidence stems primarily from the fact that the point source is seen in both the F450W and F814W (2001 November 7–8) images, \( \text{and it is not seen in the F606W (1994 November 4) WF4} \)

image (Fig. 15). Note how close the position is to the chip edge (<50 pixels). Since HSTPhot masks the first 50 pixels from the chip edge, in this exceptional case we had to use PSF fitting in DAOPHOT/ALLSTAR (Stetson 1987, 1992) within IRAF, with a Tiny Tim PSF (Krist 1995) for both the F450W and F814W bands, and subsequently tie the results to the HSTPhot output for point sources across the rest of the unmasked chip. Finally, we transformed the resulting magnitudes to standard \( B \) and \( I \) via synthetic photometry generated with the STSDAS package SYNPHOT and the Bruzual Spectral Atlas (see Filippenko et al. 1995; Van Dyk et al. 2002a). We estimate that the SN had \( B = 22.78 \pm 0.05 \) and \( I = 20.97 \pm 0.04 \) mag on 2001 November 8.

A progenitor is not detected on the pre-SN image, to \( m_{\text{phot}} \approx 24.7 \) mag. The Galactic \( A_V = 0.15 \) mag, but we can use the F450W and F814W image color information to investigate the extinction local to the SN. Figure 16 illustrates the color-magnitude diagram for the SN environment, showing the SN and the three stars immediately next to the SN in Figure 14. The diagram implies that all three stars are quite luminous, intermediate in color, and young. The three stars could all be in the helium-burning phase, following the blue loop expected for massive star evolution, or they could all be very blue supergiant stars experiencing \( A_V \approx 1–1.5 \) mag. The fact that the environment appears to contain blue or yellow, young (\( \lesssim 6 \) Myr), and therefore massive, stars suggests that the SN progenitor could have been quite massive as well. For a distance of about 16 Mpc and assuming simply the Galactic value of \( A_V \), a pro-
3.11. SN 2001B in IC 391

SN 2001B was discovered by the BAO SN search (Xu & Qiu 2001) and classified as a probable SN Ib by Chornock & Filippenko (2001; note that Matheson et al. 2001c had earlier classified it as SN Ia). From a Mount Hopkins V-band image (kindly provided by T. Matheson) we measure the SN position as $\alpha = 04^h 57^m 19^s 31, \delta = +78^\circ 11^\prime 16^\prime\prime 6$, with uncertainty $\pm 0^\prime 2$. The host galaxy was imaged by GO-5104 in a single 70 s F555W exposure on 1994 February 21. We use four stars from the Mount Hopkins image to establish the astrometric grid on the WFPC2 mosaic, with total uncertainty $\pm 0^\prime 3$. Figure 17 shows the SN site on the WF3 chip. Within the error circle is a point source with $m_p = 23.38 \pm 0.18$ mag. For a distance of about 28 Mpc and Galactic $A_V = 0.42$ mag, we find $M_V \approx -9.3$ mag for this star, which we tentatively identify as the SN progenitor. Unfortunately, we do not have any color information for the candidate. However, if this star is not the progenitor, then for a detection limit $m_{F555W} \approx 24.3$ mag, the progenitor had $M_V \approx -8.4$ mag.

3.12. SN 2001ai in NGC 5278

SN 2001ai was discovered by LOTOSS (Modjaz, Li, & Schwartz 2001b) and classified as an SN Ic by Matheson et al. (2001b). From a KAIT image we measure the SN position as $\alpha = 13^h 41^m 39^s 37, \delta = +55^\circ 40^\prime 05^\prime\prime 8$, with uncertainty $\pm 0^\prime 3$. The host galaxy was imaged in F255W, F300W, and F814W (total exposure times 1400, 1500, and 260 s, respectively) on 2000 December 18 by GO-8645. Since the stars seen in the F814W mosaic are too faint for 2MASS counterparts, we establish the astrometric grid from a Palomar V-band image, with uncertainty $\pm 0^\prime 3$. We show in Figures 18 and 19 the SN site on the WF3 chip, with total uncertainty $\pm 0^\prime 4$, in F814W and F300W, respectively.

Two objects which HSTphot considers extended, A and B, are detected in both F300W and F814W at the periphery of the error circle, with $m_{F300W} = 21.10 \pm 0.01, m_{F814W} = 21.35 \pm 0.01$ mag, and $m_{F300W} = 20.96 \pm 0.01, m_{F814W} = 22.14 \pm 0.01$ mag, respectively. Additionally, object C, considered stellar by HSTphot, is detected at F300W only at the southern edge of the circle, with $m_{F300W} = 22.57 \pm 0.32$ mag. (The F255W image is not of sufficiently high S/N to provide additional information on the environment; the detection limit is $m_{F255W} \approx 20.5$ mag.) No other objects are detected within the error circle to $m_{F300W} \approx 23.2$ and $m_{F814W} \approx 23.9$ mag.

The SN host is quite distant ($\sim 120$ Mpc), and for Galactic $A_V = 0.03$ mag, objects A and B have $M_V \approx -14.0, (U-I)^0 \approx -0.3$ mag, and $M_V \approx -13.3, (U-I)^0 \approx -1.2$ mag, respectively.
Object C has $M_V \approx -12.8$, $(U-I)^0 \approx -1.3$ mag (based on the $m_{F555W}$ detection limit), which is likely too bright for a single star. At 120 Mpc, in this case what HSTphot considers stellar is probably still an extended object (e.g., a compact cluster). The progenitor could have been associated with one of these three objects, which are probably star clusters, and was not resolved. Alternatively, the progenitor was not associated with these objects and also not detected, to $M_V^0 \approx -11.5$ mag, the upper end of which greatly exceeds even the most luminous supergiants. The relatively unrestrictive color limit for an undetected progenitor is $(U-I)^0 \approx -0.3$ mag.

3.13. SN 2001ci in NGC 3079

SN 2001ci was discovered on 2001 April 25 by LOTOSS using KAIT (Swift, Li, & Filippenko 2001). Swift et al. remarked on the low apparent luminosity of the SN. Filippenko & Chornock (2001) identified it as an SN Ic, but possibly extinguished by $A_V \approx 5-6$ mag. We measure from a KAIT image a position of $\alpha = 10^\mathrm{h}01^\mathrm{m}57^\mathrm{s}.21$, $\delta = +55^\circ41'14''.0$, with uncertainty $\pm 0''.3$. The host galaxy was imaged on 2001 January 21 in F606W (560 s) by GO-8597, and on 1999 March 4 by GO-7278 in F547M (320 s) and F814W (140 s), all pre-SN observations. The stars on the F606W mosaic were too faint for 2MASS, so we used a deep Palomar $V$-band image to establish the astrometric grid, with uncertainty $\pm 0''.2$, and total uncertainty $\pm 0''.3$. The host was also imaged on 2001 December 9, well after discovery, in F300W ($\sim U$; 800 s) by GO-9124, but the SN is not detected to $m_{F300W} \geq 23.5$ mag. We show in Figure 20 the SN site on the F814W WF3 chip. A hint of an object can be seen within the error circle, but no star is detected by HSTphot to $V \geq 24.7$, $V-I \leq 1.8$ mag, based on the F547M and F814W images. The F606W limit is significantly deeper, at $V \approx 26.4$ mag. Assuming the above range in extinction and a distance of about 21 Mpc, the F606W limit corresponds to $M_V^0 \approx -10.2$ to $-11.2$ mag. The color limit is $(V-I)^0 \approx -0.2$ to $-0.6$ mag.

3.14. SN 2001du in NGC 1365

SN 2001du was visually discovered by Evans (2001), about 90' west and 10' south of the nucleus of the nearby barred spiral galaxy NGC 1365. The SN was classified as Type II-P by Wang et al. (2001). We have independently measured the position from three different SN images available on the Internet: an image by G. Bock, a deeper image by T. Dobosz, and an image obtained with the YALO 1 m at CTIO. We derive three slightly different positions, respectively: $\alpha = 3^\mathrm{h}33''29'15', \delta = -36^\circ08'32''.0$; $\alpha = 3^\mathrm{h}33''29'14', \delta = -36^\circ08'32''.0$; and $\alpha = 3^\mathrm{h}33''29'15', \delta = -36^\circ08'31''.5$. (Uncertainties in each are $\pm 0''.7$, $\pm 0''.5$, and $\pm 0''.3$, respectively.) Together, these measurements differ from each other by $\pm 0''.7$.
Fig. 18.—Site of SN 2001ai in NGC 5278 in an archival 260 s F814W image from 2000 December 18. The error circle has radius 0.7. Objects A and B along the edge of the circle are indicated with tick marks.

The measurements all differ by $\pm 0.5$ from that measured by Jacques (2001). We adopt the position measured from the YALO image, with the smallest error. This adopted position is $\sim 0.7$ from the position we initially quoted in Van Dyk et al. (2001); the difference is likely due to the improved astrometric solution, but is consistent with the overall uncertainties discussed here. Given the uncertainty in the measured positions, and the relative disagreement with previously measured positions, we adopt a total positional uncertainty of $\pm 0.8$.

The SN site is in 100 s F336W, F555W, and F814W exposures obtained by GTO-5222 on 1995 January 15. (Unfortunately, the Cepheid Key Project [Silbermann et al. 1999] very deep images are of the opposite arm of NGC 1365.) We could apply the 2MASS astrometric grid using only three relatively bright stars on the F555W mosaic. We estimate the uncertainty in this application, based on one other object on the mosaic, and find $\pm 0.4$, which leads to a grand total uncertainty of $\pm 0.9$. Figure 21 shows the SN site on the F555W WF3 chip. Three objects, A–C, are detected within the error circle (a source that looks somewhat extended is toward the center of the circle, but it is undetected by HSTphot). Object A, to the south, is blue, with $m_{F555W} = 24.30 \pm 0.21$ mag and no detection at F814W; object B, to the west, is also blue, with $m_{F555W} = 25.02 \pm 0.32$ mag and no F814W counterpart; and object C, to the east, is relatively red, with $V = 24.44 \pm 0.23$ and $V-I = 1.03 \pm 0.30$ mag. (The F336W exposures are of insufficient S/N to show any object at the SN site.) Since SN 2001du is of Type II-P, we assume that of the three detected...
Fig. 21.—Site of SN 2001du in NGC 1365 in an archival 100 s F555W image from 1995 January 15. The error circle has radius 0′.9. Three stars, A–C, within the circle are indicated with tick marks. Stars A and B are blue, while star C, with $M_V \approx -6.9$ and $(V-I)_0 \approx 1.0$ mag, is red, and is therefore a possible candidate for the progenitor of this SN II-P.

The Galactic extinction toward the host is $A_V = 0.07$ mag, but we possibly can use the color information from the F555W and F814W images to estimate the extinction local to the SN, as well as study the properties of the SN’s stellar environment. Figure 22 shows the $(V-I, V)$ color-magnitude diagram for the environment. The reddish progenitor candidate, star C, is indicated. It is interesting that no red (M-type) supergiant stars, the presumed SN II progenitors, with $(V-I) \approx 1.8$ and $V \approx 25$ mag, are detected in the environment, likely because of the low S/N of these images. It is also notable that many of the detected stars, including star C, have $V \approx 24.7$ and $V-I \approx 1.1$ mag. These presumably K-type supergiants either all have ages $\sim 12$–16 Myr and are in the blue loop core He-burning phase, or they are intrinsically far bluer and younger supergiants experiencing similar, larger amounts of extinction, $A_V \approx 2.5$ mag.

Given the distance modulus $\mu = 31.3$ mag to NGC 1365 determined from HST observations of Cepheids (Silbermann et al. 1999) and only the Galactic extinction, if star C is the progenitor it has $M_V^0 \approx -6.9$ and $(V-I)^0 \approx 1.0$ mag. With possibly higher local extinction, $A_V \approx 2.5$ mag, this becomes $M_V^0 \approx -9.4$ and $(V-I)^0 \approx 0.0$ mag. We consider it more likely that the relevant archival data were just not sensitive enough to detect the true progenitor of SN 2001du. Assuming only Galactic extinction, the progenitor had $M_V^0 \approx -6.3$ and $(V-I)^0 \approx 1.5$ mag. Program GO-9041 has imaged SN 2001du in several bands with WFPC2, and these data will be public in late November 2002. At that time, or possibly earlier, we will know the exact location of the SN and potentially learn more about the nature of the progenitor.

3.15. SN 2001is in NGC 1961

SN 2001is was independently discovered by both the BAO and LOTOSS searches (Qiu et al. 2001). Benetti et al. (2001) identified it as an SN Ib, with possible residual H contamination. From a KAIT image we measure the SN position as $\alpha = 05^h 42^m 09^s.12$, $\delta = +69^\circ 21^\prime 54^\prime.5$, with uncertainty $0^\prime.4$. The host galaxy was imaged (GO-5419) on 1994 August 28 in a cosmic-ray split F218W exposure (1800 s total) and in a single 300 s F547M exposure. The host was also imaged deeply by GO-9106 in the FR680N and F547M bands (4000 s each) on 2001 July 14. (The low S/N of the FR680N images near the SN site does not make them particularly useful.) The KAIT image was sufficiently deep that we could identify some of the stars in each of the F547M mosaics, with astrometric uncertainty $0^\prime.2$, for a total uncertainty of $\pm 0.4$ in the SN’s position on the mosaic. In Figure 23, we show the SN site on the deep F547M WF3 chip. Two stars, A and B, are detected...
within the error circle with \( m_{\text{F547M}} = 26.11 \pm 0.27 \) and \( 25.77 \pm 0.20 \) mag. Assuming a distance of about 64 Mpc and Galactic \( A_v = 0.41 \) mag, we find \( M_v^0 \approx -8.3 \) and \( -8.7 \) mag for the two stars, respectively, either of which could be the progenitor. If neither of these stars is the progenitor, then for a detection limit of \( m_{\text{F547M}} \approx 26.4 \) mag, the progenitor had \( M_v^0 \approx -8.0 \) mag.

## 4. DISCUSSION

In Table 2, we summarize the results of our search for the progenitors of core-collapse SNe. For SNe with candidate progenitor identifications, we have also included, in parentheses, the limits on the absolute magnitude and color of a possible progenitor, if the candidate we have identified is not the actual progenitor. It should be noted that for all the magnitude and color estimates, we have assumed possibly inaccurate distance estimates and, in most cases, only the Galactic component to the extinction toward the SN. Consequently, we may have either underestimated or overestimated the absolute magnitude, or limits on the absolute magnitude, of candidate progenitors. Extinction local to the SNe within the host galaxies themselves will only lead to higher absolute brightnesses and to bluer intrinsic colors, or color limits, for all these objects. At the least, we provide the measured magnitudes and magnitude limits for the SN progenitors, based on the HSTphot output, so that, with additional information, the reader can make his or her own estimations. Below, we briefly interpret our results, but we eschew transforming the observed magnitudes and colors into intrinsic properties, such as bolometric luminosity and surface temperature, for lack of adequate information about the stars.

The candidate SNe II progenitors of SNe 1999br, 1999ev, and 2001du all have absolute magnitudes \( (M_v^0 \approx -5.9 \) to \(-6.9 \) that are consistent with the known red supergiants in the Galaxy. All of the magnitude limits for the other SNe II are also consistent with supergiant stars. The only candidate with intrinsic color information, the progenitor candidate for SN 2001du, has a \((V-I)^0\) value more consistent with an early K spectral type (e.g., the Vilnius spectral colors in Bessell...

### Table 2

**Summary of Progenitor Properties**

| SN     | Absolute Magnitudea | Colora (mag) |
|--------|---------------------|--------------|
| SNe II |                     |              |
| 1998Y  | \( M_v^0 \approx -6.9 \) | \((V-I)^0 \approx -0.5 \) |
| 1999an | \( M_v^0 \approx -6.2 \) | \((V-I)^0 \approx -0.9 \) |
| 1999br | \( M_v^0 \approx -5.9 \) | \((V-I)^0 \approx -1.0 \) |
| 2001da | \( M_v^0 \approx -6.9 \) | \((V-I)^0 \approx -1.0 \) |
| 2001B  | \( M_v^0 \approx -6.3 \) | \((V-I)^0 \approx -1.5 \) |
| SNe Ib/c |                   |              |
| 1999ba | \( M_v^0 \approx -7.5 \) | \((U-B)^0 \approx -0.3 \) |
| 1999da | \( M_v^0 \approx -7.3 \) | \((V-I)^0 \approx -1.5 \) |
| 1999dd | \( M_v^0 \approx -8.7 \) | \((V-I)^0 \approx -1.5 \) |
| 2000C  | \( M_v^0 \approx -8.9 \) | \((V-I)^0 \approx -1.2 \) |
| 2000da | \( M_v^0 \approx -5.5 \) | \((V-I)^0 \approx -1.5 \) |
| 2000ew | \( M_v^0 \approx -6.5 \) | \((V-I)^0 \approx -1.5 \) |
| 2001B  | \( M_v^0 \approx -9.3 \) | \((V-I)^0 \approx -1.5 \) |
| 2001ai | \( M_v^0 \approx -8.4 \) | \((V-I)^0 \approx -1.5 \) |
| 2001ci | \( M_v^0 \approx -11.5 \) | \((V-I)^0 \approx -1.5 \) |
| 2001is | \( M_v^0 \approx -8.3 \) | \((V-I)^0 \approx -1.5 \) |

* The distance to the host galaxy is generally derived from the heliocentric radial velocity corrected for Local Group infall into the Virgo Cluster given in the LEDA database, with distance scale 65 km s\(^{-1}\) Mpc\(^{-1}\). The extinction and reddening to the SN are generally assumed the Cardelli et al. 1989 reddening law. See text for details.

b We could not locate SN 1998Y in our own Snapshot (GO-8602) images, nor could we determine a reliable position for the SN progenitor in the archival images.

a We have also included, in parentheses, the upper limits on the absolute magnitude and color of a possible progenitor here and throughout the table.
for SNe Ic. Nomoto et al. (1994) explored a binaries (e.g., Nomoto et al. 1990) end up with too much helium stripped of much of their helium could lead to SNe Ic; however, must be similar as well. Wolf-Rayet stars that have been analysis of SN Ib spectral data, that the masses and kinetic energies to SNe Ib. However, Branch et al. (2002) find, from their analysis, a wide orbit including a more massive main-sequence second-ary (e.g., van den Heuvel 1994). Both mechanisms could lead to SNe Ib. However, Branch et al. (2002) find, from their analysis of SN Ib spectral data, that the masses and kinetic energies among SNe Ib are similar, implying that progenitor masses must be similar as well. Wolf-Rayet stars that have been stripped of much of their helium could lead to SNe Ic; however, model light curves decline too slowly, compared to observations (Woosley, Langer, & Weaver 1993). Low-mass helium stars in binaries (e.g., Nomoto et al. 1990) end up with too much helium for SNe Ic. Nomoto et al. (1994) explored a $\sim 2-3 \, M_\odot$ C+O star (which originally evolved from a $13-18 \, M_\odot$ main-sequence star) in a close binary as the progenitor of the SN Ic 1994I in M51. Their model, possibly including a common-envelope phase, involves two episodes of mass transfer with a secondary, which eventually evolves to be a low-mass main sequence star, a neutron star, or a white dwarf. All of these scenarios involve compact stars, which are likely not particularly luminous; Barth et al. (1996) place an upper limit of $M_V \approx -7.3$ mag on the SN 1994I progenitor. As Podsiałdowski et al. (1992) point out, mass transfer, in fact, could make the secondary more massive and more luminous when the primary explodes, meaning that a detected “progenitor” could actually be the companion star. The candidate progenitor for the SN Ic 1999bu is quite luminous, with $M_V \approx -7.5$ mag, which is consistent with the upper limit for the SN 1994I progenitor mentioned above. The candidate progenitors for the SNe Ib 2001B and 2001is are also very luminous, with $M_V \approx -8$ to $-9$ mag. The known Wolf-Rayet stars in the Galaxy have absolute magnitudes spread over a large range, $M_V \approx -2$ to $-8$ mag (van der Hucht 2001). The SN Ib progenitor candidate luminosities are near or slightly above the upper end of this luminosity range. Therefore, it is possible that these two SNe Ib arose from Wolf-Rayet stars. (However, with the uncertainties in the distances to and reddening within the host galaxies, these absolute magnitudes may actually fall outside the Wolf-Rayet luminosity range, i.e., they would be too bright.) The luminosities for these SN Ib progenitor candidates are also consistent with those of other, less evolved, presumably blue or yellow supergiants (Humphreys & Davidson 1979). Alternatively, it is possible that these candidates are not the progenitors, but instead multiple star systems or compact star clusters.

Generally, the absolute magnitude limits for all other SNe Ib/c (the brightness limits for SNe 2001ai and 2001ci are not very restrictive) are consistent both with the range of Wolf-Rayet magnitudes and also with expectations for interacting binary models. The intrinsic color limits, although also usually not very restrictive, are consistent with blue or yellow stars. The most restrictive color limits are for the progenitors of SNe 1999ec and 2001ci (if, in this case, the extinction estimate $A_V \approx 5-6$ mag is, in fact, correct): taken together, these limits imply that the progenitors had spectral types of A-type or earlier (Bessell 1990) and are also consistent with the range of $B-V$ (about $-0.5$ to $-0.1$ mag) for Galactic Wolf-Rayet stars (van der Hucht 2001). The host galaxy of SN 2001ci, NGC 3079, is seen nearly edge-on, so it is possible that the SN progenitor could have been a Wolf-Rayet star exploding while obscured by or embedded in dust.

To some extent, our search was not fully satisfying. Although it is true that, compared with the case of Van Dyk et al. (1999a), the HST archive is currently much richer in pre-SN host galaxy images, which may potentially contain SN progenitors, and more importantly, post-SN images in which the fading SNe may be recovered, the quality of these data is such that the SN or number of filters used are generally still not ideal. The data in our sample are not yet sensitive enough for us to place more stringent constraints on the competing models for SNe Ib/c. The HST archive will steadily grow, however, as observations continue after the recent refurbishment mission. These new observations will also include images of galaxies with the superior Advanced Camera for Surveys (ACS). Additionally, new nearby SNe will be discovered by LOSS/LOTOS and other SN searches, greatly expanding the potential sample. We intend to further exploit the HST archive to continue to search for core-collapse SN progenitors; the future looks bright for this subject.

5. CONCLUSIONS

We have searched for the progenitor stars of 16 core-collapse SNe using archival HST WFPC2 images. The sample includes six SNe II and 10 SNe Ib/c. We may have identified the progenitors of the SNe II 1999br, 1999ev, and 2001du as supergiant stars with $M_V \approx -6$ mag in all three cases. We may also have identified the progenitors of the SNe Ib 2001B and 2001is as very luminous supergiants with $M_V \approx -8$ to $-9$ mag, and possibly the progenitor of the SN Ic 1999bu as a supergiant with $M_V \approx -7.5$ mag. If these identifications can be verified, this more than doubles the number of known SN progenitors from five to 11. For all other SNe in our sample, we could only place limits on the progenitor absolute magnitude and color (when multiband images were available). We have also recovered SNe 1999dn, 2000C, and 2000ew at late times. Unfortunately, the pre-SN images for these recovered SNe did not show a progenitor candidate at the SN position.

The possible detections and constraints on the SN II pro-
genitors are broadly consistent with red supergiants as pro-
genitor stars, although the progenitor candidates are not as red
as would be expected, with their colors implying spectral types
typically earlier than M. The SN Ib progenitor candidates may
well be Wolf-Rayet stars, although possibly at the upper lu-
minosity end for known stars of this kind. The lone SN Ic
progenitor candidate is consistent with a luminous supergiant
star. In general, we cannot place rigorous constraints on either
the Wolf-Rayet star or massive interacting binary models for
SN Ib/c progenitors, based on these data. For both the SNe II
and Ib/c, uncertainties in the host galaxy distances and extinction
toward the SNe also limit what conclusions we can draw
about the progenitor stars. However, from purely environmental
considerations, our results are consistent with those of Van Dyk
et al. (1999a), who found that SNe Ib/c seem to be more closely
associated with massive stellar regions than is true for SNe II;
five of the SNe Ib/c in our sample (SNe 1999ec, 2000C, 2000ew, 2001ai, and 2001is) occurred very near bright, possi-
bly blue and young star clusters (the cluster near SN 2000C,
based on the F300W image, is quite blue, and the cluster near
SN 2000ew, based on the color-magnitude diagram, is quite young).
Again, the statistics are still small, but this continues
to suggest that at least some SN Ib/c progenitors may be more
massive, in general, than SN II progenitors, consistent with the
Wolf-Rayet model.

A current program (GO-9353) is imaging six of the SNe in
our sample (1999an, 1999br, 1999ev, 2000ds, 2000ew, and
2001B) in multiple bands with ACS, to attempt to recover them
at late times, with the same aim of matching the pre-SN and
post-SN images to identify the SN progenitor. Similarly, pro-
gram GO-9041 has imaged SN 2001du with WFPC2, but the
data are not yet public. For SNe 1999an, 2000ds, and 2000ew,
we have already likely recovered SN 2000ew, and we have
already shown here that the pre-SN images are simply not of
sufficient S/N to detect each SN progenitor. For SNe 1999br,
1999ev, 2001B, and 2001du, the new observations from these
programs will be quite revealing: if the SNe are actually re-
covered, they may or may not match up positionally with the
progenitor candidates that we have identified.

In this paper, we have made some progress toward a statisti-
cally significant sample of core-collapse SN progenitors di-
rectly identified on HST image data. However, the limitations
of the data continue to be the restricted field of view, low
S/N, and poor color coverage. With the full operation of the
newly commissioned ACS aboard HST, and with additional
galaxies observed using WFPC2 as well, the amount of avail-
able archive data will continue to grow, providing for larger
SN samples in the future.

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Addendum

“A Search for Core-Collapse Supernova Progenitors in Hubble Space Telescope Images”
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The multiband GO-9041 images of SN 2001du in NGC 1365, obtained by the Hubble Space Telescope on 2001 November 26 (see Fig. 24), have recently become publicly available and show the SN nearly coincident with the blue object B (see § 3.14 in our original paper). A detailed analysis of these images is in preparation.

Fig. 24.—SN 2001du, as seen in a 40 s F555W image obtained on 2001 November 26 for HST program GO-9041. The SN had $V = 15.3$ mag. We have determined that the SN occurred less than 1 WF-chip pixel northeast of object B.