

## THE BIRTH PLACE OF THE TYPE IC SUPERNOVA 2007gr

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### ABSTRACT

We report our attempts to locate the progenitor of the peculiar Type Ic SN 2007gr in *Hubble Space Telescope* (*HST*) preexplosion images of the host galaxy, NGC 1058. Aligning adaptive optics Altair/NIRI imaging of SN 2007gr from the Gemini (North) Telescope with the preexplosion *HST* WFPC2 images, we identify the supernova (SN) position on the *HST* frames with an accuracy of 20 mas. Although nothing is detected at the SN position, we show that it lies on the edge of a bright source,  $134 \pm 23$  mas (6.9 pc) from its nominal center. On the basis of its luminosity, we suggest that this object is possibly an unresolved, compact, and coeval cluster and that the SN progenitor was a cluster member, although we note that model profile fitting favors a single bright star. We find two solutions for the age of this assumed cluster:  $7 \mp 0.5$  Myr and 20–30 Myr, with turnoff masses of  $28 \pm 4 M_{\odot}$  and  $12\text{--}9 M_{\odot}$ , respectively. Preexplosion ground-based *K*-band images marginally favor the younger cluster age/higher turnoff mass. Assuming the SN progenitor was a cluster member, the turnoff mass provides the best estimate for its initial mass. More detailed observations, after the SN has faded, should determine whether the progenitor was indeed part of a cluster and, if so, allow an age estimate to within  $\sim 2$  Myr, thereby favoring either a high-mass single star or lower-mass interacting binary progenitor.

*Subject headings:* galaxies: individual (NGC 1058) — stars: evolution — supernovae: general —  
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*On-line material:* color figure

### 1. INTRODUCTION

Direct detection of the progenitors of core-collapse supernovae (CCSNe) in archival observations of nearby galaxies, particularly those from the *Hubble Space Telescope* (*HST*), has recently proved successful. Luminous red supergiant progenitors of the hydrogen-rich Type II-P SNe have now been identified (Smartt et al. 2004; Maund et al. 2005a; Li et al. 2006), with initial masses above  $8 M_{\odot}$ . However, the progenitors of Type Ib/c SNe, believed to be the cores of massive stars that have lost their outer envelopes, have so far eluded discovery (e.g., Maund & Smartt 2005). The two nearest Type Ib/c SNe with deep preexplosion images (SN 2002ap in M74 at  $\sim 9$  Mpc and SN 2004gt in NGC 4038 at  $\sim 14$  Mpc) had no progenitor detected (Maund et al. 2005b; Gal-Yam et al. 2005; Crockett et al. 2007). The progenitors were limited to either lower-mass stars that were stripped of their hydrogen-rich envelope via binary interaction or single stars with masses  $>30\text{--}40 M_{\odot}$  for which radiatively driven mass loss may have been sufficient to remove the outer layers. In the case of the Type Ib SN 2006jc, the progenitor was discovered in an luminous blue variable (LBV)-like outburst state 2 yr before explosion, suggesting that it was a very massive star (Pastorello et al. 2007). Some fraction of Type Ib/c SNe

also produce gamma-ray bursts, hence any information on their progenitors would be critical for the field (Woosley & Bloom 2006).

In this Letter we study the explosion site of SN 2007gr in NGC 1058 ( $10.6 \pm 1.3$  Mpc; Pilyugin et al. 2004) and confirm it as a Type Ic. SN 2007gr was discovered by Madison & Li (2007) on 2007 August 15.15 UT, located at  $\alpha_{J2000} = 2^{\text{h}}43^{\text{m}}27^{\text{s}}.98$ ,  $\delta_{J2000} = +37^{\circ}20'44''.7$ . Chornock et al. (2007) spectroscopically classified SN 2007gr as Type Ib/c but suggested that the presence of strong O I  $\lambda 7774$  and Ca II IR triplet absorptions were similar to those features observed in Type Ic SNe. Using the relation between the equivalent width of the Na I D interstellar lines and the reddening (Turatto et al. 2003), we obtain a reddening toward SN 2007gr of  $E(B - V) = 0.08$  (S. Valenti et al., in preparation). Where standard filter sets were employed, extinctions were calculated using the laws of Cardelli, Clayton, & Mathis (1989) and for *HST* observations using the  $A_{\lambda}/E(B - V)$  relations of Van Dyk et al. (1999).

### 2. OBSERVATIONS AND DATA ANALYSIS

The preexplosion site of SN 2007gr was observed on 2001 July 3 with the Wide Field and Planetary Camera 2 (WFPC2) on board *HST* as part of programme GO-9042. Observations were made in the F450W and F814W filters (460 s each), and photometry was carried out using the point-spread function (PSF)-fitting photometry package HSTphot (Dolphin 2000). Further ground-based observations of NGC 1058 were found in the 4.2 m William Herschel Telescope (WHT) and the 2.5 m Isaac Newton Telescope (INT) archives. The WHT INGRID *K*-band images from 2001 October 6 had a total exposure time of 1320 s and an image resolution of  $1.2''$ . The INT WFC images from 2005 January 13 were taken using *r'*-band (180 s) and narrow H $\alpha$  filters (600 s) with image quality of  $0.9''$ .

Ground-based adaptive optics (AO) observations of SN 2007gr were taken on 2007 August 19 using Altair/NIRI on the

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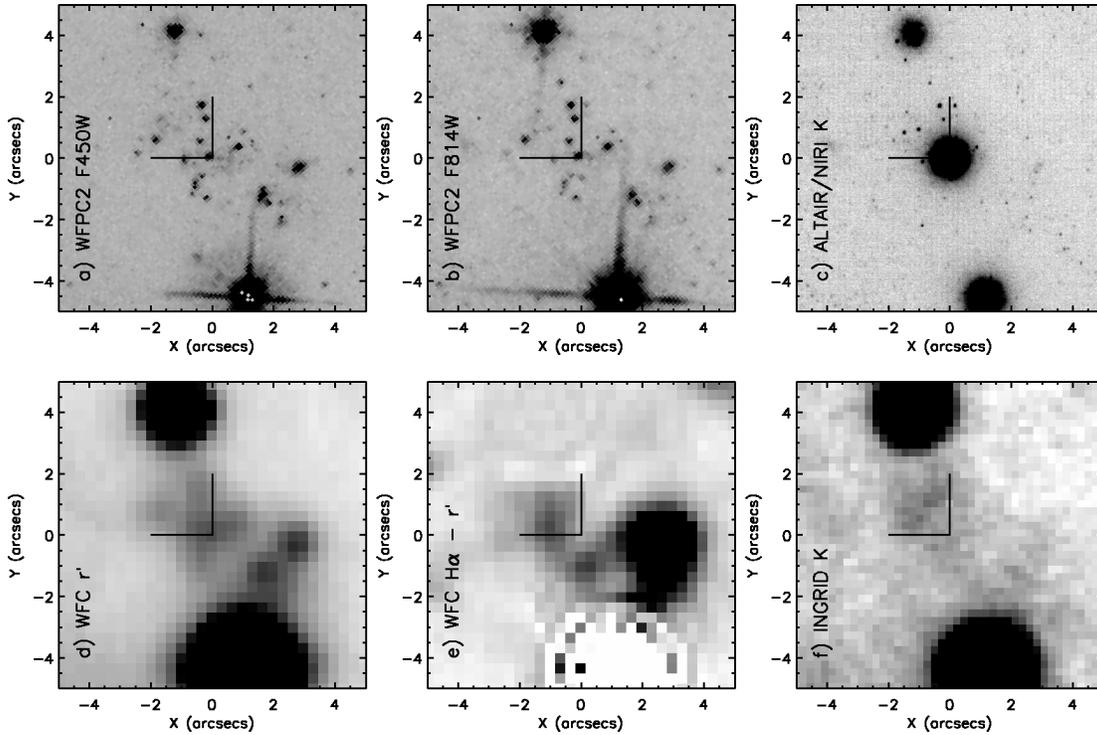


FIG. 1.—Pre- and postexplosion images of the site of SN 2007gr in NGC 1058. Each of the images is centered on the SN position and oriented such that north is up and east is to the left. The position of SN 2007gr is located at the center of each of the panels indicated by the cross hairs. (a) Preexplosion HST+WFPC2 F450W image. (b) Preexplosion HST+WFPC2 F814W image. (c) Postexplosion Gemini+Altair/NIRI  $K$ -band image with the SN clearly visible. (d) Preexplosion INT + WFC  $r'$ -band image. (e) Preexplosion INT+WFC  $H\alpha - r'$  image. (f) Preexplosion WHT+INGRID  $K$ -band image.

8.1 m Gemini (North) Telescope. Exposures totalling 930 s were acquired in the  $K$  band using the SN as the natural guide star. The reduced image is of exceptionally high quality, showing near-diffraction-limited resolution of  $0.08''$ , with a pixel scale of  $0.022''$  providing excellent sampling of the PSF. Figure 1 shows that this Gemini image even resolves some objects that appear blended in the *HST* data, an effect of the  $0.1''$  pixel scale of the WFPC2 chip. In order to confirm the classification of the SN, a spectrum was obtained on 2007 September 11 using the WHT equipped with ISIS (R300B+R158R).

The site of SN 2007gr fell on the WF2 chip of the preexplosion WFPC2 observations. To determine the position of the SN site accurately on these images, we calculated a transformation to map the coordinate system of the postexplosion Gemini image to the WFPC2 preexplosion frames using the IRAF GEOMAP task. Positions of 19 stars common to both the WFPC2 F814W and Gemini  $K$ -band images provided a general geometric transformation (involving shifts, scales, and rotation) with an rms error of  $\pm 20$  mas. The SN position was measured in the Gemini image and transformed to the coordinate system of the F814W preexplosion frame, yielding a pixel position on the WF2 chip of [250.65, 118.34]. Figures 1a and 1b show that the SN site is very close to, but not coincident with, an object that is bright in both the F450W and F814W images. Its position was measured as [250.10, 119.56] with an accuracy of  $\pm 11$  mas. The SN site is therefore  $0.121''$  west and  $0.056''$  south of this bright object. Li et al. (2007) give a position for SN2007gr on the WFPC2 images that is around 66 mas farther north than our position, meaning our respective positions are not coincident within the combined errors (combined error from this study  $\pm 23$  mas; Li et al. claim  $\pm 20$  mas). We suggest that the Li et al. error has been underestimated given that they used a MEGACAM image of the SN from the Canada-France-Hawaii Telescope to perform differential astrometry, which is of much lower resolution than our Gemini data.

The position of the SN on the INT and WHT preexplosion observations was determined using a similar method. The INT  $r'$ -band image (Fig. 1d) shows significant flux at the SN position, but this is almost certainly due entirely to the resolved sources observed in the *HST* frames. Subtraction of the  $r'$ -band continuum from the  $H\alpha$  image identifies regions of strong  $H\alpha$  emission. Since hot OB-type stars are required to ionize the hydrogen gas,  $H\alpha$  emission is generally associated with clusters of young, massive stars. The image subtraction package ISIS 2.2 (Alard & Lupton 1998; Alard 2000) was used to match the PSF, flux, and background of the INT  $r'$ -band image to its  $H\alpha$  counterpart. Figure 1e shows several regions of quite strong emission surrounding the SN site, but none exactly coincident with its position. In the WHT  $K$ -band image (Fig. 1f), nothing is visible at or near the SN position.

### 3. OBSERVATIONAL RESULTS AND DISCUSSION

SN2007gr occurred in a large, extended star-forming region that in Figure 1 is at least  $5''$  in diameter (250 pc). Within this there are bright sources, some of which are pointlike and others which are clearly extended. Most of these are likely to be compact stellar clusters rather than single individual supergiants. Compact star clusters tend to be clustered together into large star-forming complexes of order 50–300 pc, and the recent study of the cluster complexes in M51 shows many that are morphologically similar to the region hosting SN 2007gr (Bastian et al. 2005). HSTphot photometry of the preexplosion WFPC2 observations gave apparent magnitudes for the bright object close to the SN site of  $21.47 \pm 0.02$  for F450W and  $20.89 \pm 0.02$  for F814W. Converting these to absolute standard magnitudes using the distance to NGC 1058 and extinction corrections (§ 1) and the color corrections of Maund & Smartt (2005) gave  $M_B = -8.99$  and  $B - I = 0.42$ . If it is a single star, it is a 30–40  $M_{\odot}$  post-main-sequence supergiant star or a more massive but ex-

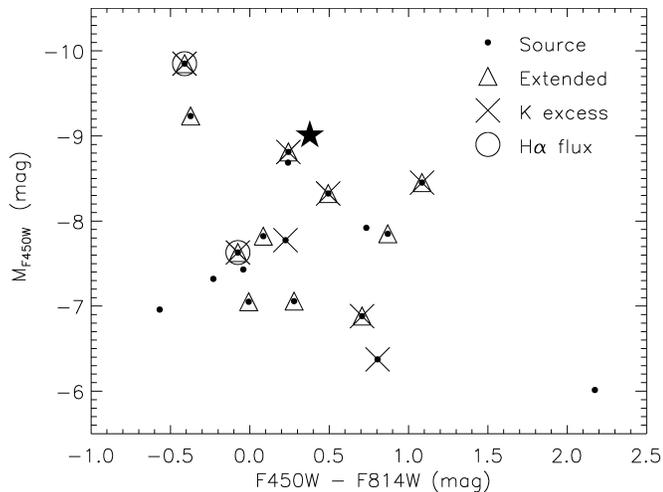


Fig. 2.—Color-magnitude diagram of sources within a radius of approximately  $3''$  (150 pc) of the SN position. Photometry is from the WFPC2 F450W and F814W preexplosion observations. All sources are marked by a filled circle. Objects that ISHAPE measured as extended are marked with triangles, those with  $K$ -band excesses of  $>0.5$  mag when compared to single stellar colors are marked with crosses, and those associated with strong  $H\alpha$  emission are indicated by open circles. The bright object closest to the SN position is marked with a filled star. Bastian et al. (2005) suggest that anything brighter than  $M_V < -8.6$  in these star-forming complexes is likely to be an unresolved cluster rather than a single, massive star.

tinguished ( $A_V \geq 1$  mag) main-sequence object. Such bright, single stars are not without precedent in star-forming galaxies (e.g., Bresolin et al. 2001), but they are few in number in any typical spiral owing to the short lifetimes of the blue-yellow supergiant phase (e.g., Eldridge & Tout 2004).

Surrounding the SN location are several other objects of similarly high luminosity that have colors consistent with O- to F-type supergiants (Fig. 2). It is unlikely that one would observe such a large number of extremely massive stars during this very short evolutionary supergiant phase in such a small surface area of the disk. Bastian et al. (2005) suggest that sources brighter than  $M_V < -8.6$  are most probably clusters. Several of the objects appear extended, implying that they are most probably not single stars. Most, however, including the bright source nearest the SN location, are not significantly broader than the stellar PSF (FWHM  $\sim 1.5$  pixels [ $0.15''$ ]), which at a distance of 10.6 Mpc corresponds to 7.7 pc. Given its absolute magnitudes and its proximity to the SN site ( $\sim 6.9$  pc), one could suggest that this bright object is a coeval cluster of diameter less than  $\sim 7.7$  pc, which hosted SN 2007gr. If it could be confirmed as such a cluster, this is potentially a powerful way of determining the initial mass of the SN progenitor.

In an attempt to constrain the true spatial extent of this object and others, we used the ISHAPE routine, part of the BAOlab package (Larsen 1999, 2004). Larsen (2004) suggests that ISHAPE can limit the intrinsic size of a significantly detected source ( $S/N \sim 50 \sigma$ ) down to  $\sim 10\%$  of the PSF FWHM, which here corresponds to  $\sim 1$  pc. Elliptical Moffat profiles with a power-law index of  $-1.5$  were convolved with Tiny Tim (Krist & Hook 1997) WFPC2 PSFs and fitted to all the objects within  $3''$  of the SN position. Those sources that are detected at the  $>10 \sigma$  level and have fitted FWHM values  $>0.15$  pixels ( $10\%$  of the PSF FWHM) in one or both of the *HST* observations are identified as extended in Figure 2. The bright source nearest the SN position is best fit with a delta function, suggesting that its diameter is no larger than  $\sim 1$  pc and that it is more likely a star rather than a cluster.

However, aperture photometry of the Gemini AO image, cal-

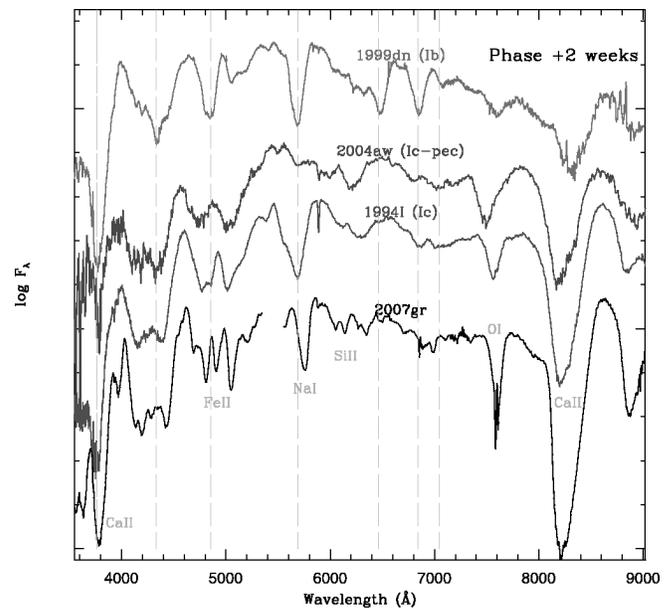


Fig. 3.—Comparison of spectra of the classical Type Ib SN 1999dn (Matheson et al. 2001; Branch et al. 2002), the peculiar Type Ic SN 2004aw (Taubenberger et al. 2006), the classical SN Ic 1994I (Filippenko et al. 1995), and SN 2007gr at 12–15 days past maximum. The spectrum of SN 2007gr shows several unusually narrow P Cygni lines. No reddening correction was applied to the spectra, while they are reported to the host galaxy rest wavelength. The vertical dashed lines mark the positions of the minima of the He I lines in the spectrum of SN 1999dn, blueshifted by about  $9500 \text{ km s}^{-1}$ . No prominent He I lines are visible in the spectrum of SN 2007gr, suggesting a Type Ic classification. [See the electronic edition of the *Journal* for a color version of this figure.]

ibrated using the two bright 2MASS sources north and south of the SN, revealed that several sources around the SN location have significant  $K$ -band excesses when compared to main-sequence and supergiant stellar colors (see Fig. 2), implying that they are not individual massive stars. Two of these sources are measured as pointlike by ISHAPE. Unfortunately, we cannot measure a  $K$ -band magnitude for the object nearest the progenitor site in the Gemini image because of the brilliance of the SN. Additionally, the  $H\alpha$  image (Fig. 1e) gives some idea of the location of the youngest OB stars within this large star-forming region. Sources in the *HST* images coincident with the  $H\alpha$  flux are marked in Figure 2. Their association with significant  $H\alpha$  emission implies that they are most likely young compact star clusters rather than single massive supergiants. We note, however, that no significant  $H\alpha$  emission is observed exactly coincident with the object nearest the SN site.

If this object is actually a massive single star rather than a cluster and the progenitor is an unrelated star within this extended star-forming region, then we can attempt to derive a luminosity limit for the undetected SN progenitor. We added fake stars of various magnitudes into the WFPC2 images at the position of the SN progenitor and tried to recover both the real and fake sources simultaneously with PSF-fitting techniques. We defined the detection limit in each filter as the magnitude of the fake source that must be added to the image in order for it to be independently detected at a position coincident with the progenitor site. The detection limits were thereby found to be  $F450W > 23.7$  ( $M_{F450W} > -6.7$ ) and  $F814W > 21.7$  ( $M_{F814W} > -8.6$ ). The detection limit for the WHT  $K$ -band image was found to be  $K > 19.7$  ( $M_K > -10.45$ ) by adding fake stars of increasing luminosity at the SN position and determining, by eye, at what magnitude an obvious source became visible.

Figure 3 shows our WHT+ISIS spectrum compared with

those of well-studied Type Ib/c SNe. The phase corresponds to about 2 weeks past maximum (S. Valenti et al., in preparation). While in SN 1999dn the He I lines are prominent, they are weak (if at all visible) in the Type Ic SNe and also in SN 2007gr, suggesting that SN 2007gr is of Type Ic. SN 2007gr shows clear similarity to SN 1994I (and, more marginally, to SN 2004aw). However, the presence of narrower features due to metals in the spectrum of SN 2007gr makes this object rather peculiar.

#### 4. IMPLICATIONS FOR THE PROGENITOR OF SN 2007gr

If we assume that the bright object closest to the SN site is a single, massive star, one can attempt to place constraints on the properties of the SN progenitor using the detection limits derived in the previous section. However, these magnitude limits are much shallower than those found for the progenitors of SN 2002ap (Crockett et al. 2007) and SN 2004gt (Maund et al. 2005b). Since the SN was of Type Ic, we can reasonably assume that its progenitor was a Wolf-Rayet (W-R) star (e.g., Eldridge & Tout 2004). Comparing our magnitude limit of  $M_{F450W} > -6.7$  with  $B$ -band photometry of W-R stars shown in Fig. 8 of Crockett et al. (2007), we see that almost all of these observed W-R stars fall below our detection limit.

If, however, the bright object closest to the SN site is an unresolved stellar cluster, then it must have a diameter of less than  $\sim 7.7$  pc (FWHM of the PSF) or perhaps less than  $\sim 1$  pc (ISHAPE analysis). In the case of the latter, the progenitor would then be on the outskirts of the cluster, although still quite possibly coeval, e.g., NGC 3603 in the Milky Way. If SN 2007gr arose from one of the most evolved stars in such a coeval cluster, then the cluster age would give an estimate of the age and initial mass of the progenitor. A similar argument has been used to estimate the progenitor mass of the Type II-P SN 2004dj (Maíz-Apellániz et al. 2004; Wang et al. 2005), through STARBURST99 population fitting of the *UBVRIJHK* spectral energy distribution. The STARBURST99 code (Leitherer et al. 1999) computes a coeval stellar population at a range of ages, with a user-defined initial mass function (IMF). A cluster of mass  $\sim 4000 M_{\odot}$  at an age of  $7 \pm 0.5$  Myr produces the absolute  $M_B = -8.99$  and  $B - I = 0.42$  (assuming solar metallicity, an upper mass limit of  $100 M_{\odot}$ , a Salpeter IMF, and a coeval burst of star formation). The Geneva stellar models imply a turnoff mass of  $25 M_{\odot}$  for the cluster, while our STARS stellar models (Eldridge & Tout 2004) imply a similar mass of  $28 \pm 4 M_{\odot}$ .

These are compatible with the minimum stellar mass thought to produce W-R stars through single stellar evolution (e.g., Massey et al. 2001; Eldridge & Tout 2004).

However, this age solution is not unique as STARBURST99 can produce  $B - I \approx 0.4$  when the cluster has evolved to 20–30 Myr. At this age the turnoff mass would be between 12 and  $9 M_{\odot}$ , much too low to produce a W-R star via single stellar evolution, and we would be forced to conclude that the progenitor was a lower-mass W-R star resulting from an interacting binary. This degeneracy can be broken only with the extra wavelength coverage of the host cluster. In particular, the  $U$  band is an excellent discriminator of age and would allow its determination to within a few Myr (Bastian et al. 2005; Maíz-Apellániz et al. 2004). At the older age the cluster becomes much redder in the NIR bands, with an estimated  $I - K = 1.1$ , and hence we would expect to detect the source at an apparent magnitude of  $K = 19.7$ . The detection limit of the WHT  $K$ -band image lies just at this level, and this would favor the younger solution, suggesting that the W-R progenitor formed from an initially 25–30  $M_{\odot}$  star.

In approximately 2 years' time, the SN will have faded enough that the putative cluster can be studied in detail, in the UV, optical, and NIR with ground-based AO imaging and hopefully a fully refurbished *HST*. With these higher spatial resolution and multiwavelength images of the immediate environment, we will be able to determine if indeed it is a compact cluster and better ascertain its properties.

Given the difficulties in pinning down the progenitors of Ib/c SNe, even with very deep preexplosion imaging (Maund et al. 2005b; Crockett et al. 2007), this particular case may offer us the best opportunity to estimate the initial mass of a Type Ic progenitor. The proximity and luminosity of SN 2007gr will make it one of the best studied and modeled Type Ic SNe to date, and it will be interesting to compare future ejecta mass estimates with our cluster turnoff mass.

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