A high angular-resolution search for the progenitor of the type Ic supernova SN 2004gt

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ABSTRACT

We report the results of a high-spatial-resolution search for the progenitor of type Ic supernova SN 2004gt, using the newly commissioned Keck laser-guide star adaptive optics system (LGSAO) along with archival *Hubble Space Telescope* data. This is the deepest search yet performed for the progenitor of any type Ib/c event in a wide wavelength range stretching from the far UV to the near IR. We determine that the progenitor of SN 2004gt was most likely less luminous than $M_V = -5.5$ and $M_B = -6.5$ magnitudes. The massive stars exploding as hydrogen-deficient core-collapse supernovae (SNe) should have lost their outer hydrogen envelopes prior to their explosion, either through winds – such stars are identified within our Galaxy as as Wolf-Rayet (W-R) stars – or to a binary companion. The luminosity limits we set rule out more than half of the known galactic W-R stars as possible progenitors of this event. In particular, they imply that a W-R progenitor should have been among the more-evolved (highly stripped, less luminous) of these stars, a concrete constraint on its evolutionary state just prior to core collapse. The possibility of a less luminous, lower-mass binary progenitor cannot be constrained. This study demonstrates the power of LGS observations in furthering our understanding of core collapse, and the physics powering supernovae, GRBs and XRFs.

Subject headings: supernovae: general

1. Introduction

Stars with masses greater than ten times the mass of the Sun end their lives with a catastrophic core collapse that explodes the stellar envelope, producing a core-collapse supernova (SN). Understanding the nature of these cosmic explosions in detail requires knowledge of the properties of their progenitor stars. The progenitors of the most common type of core-collapse SNe (hydrogen-rich or type II) have been identified (White and Malin 1987; Aldering, Humphreys, & Richmond 1994; Van Dyk, Li, & Filippenko 2003a; Smartt et al. 2003) as luminous supergiants.

By contrast, the observational constraints on the progenitors of the hydrogen-poor type Ib and Ic events (Filippekno 1997) are minimal. Previous progenitor searches (Barth et al. 1996; Smartt et al. 2002; Van Dyk, Li, & Filippenko 2003b; Maund & Smartt 2005) utilizing pre-explosion images from the ground or from *HST* have so far yielded upper limits that were not sensitive enough to constrain the nature of the exploding star. This is unfortunate, because a small fraction of these events produce, as they die, not only a SN but also a gamma-ray burst (GRB; e.g., Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Malesani et al. 2004) or an X-ray flash (XRF; Soderberg et al. 2005) – in the process, radiating an energy many times that of the brightest SNe. Constraining the properties of evolved massive stars that give rise to SNe Ib and Ic may lead to better understanding of the physics of these explosions, and may prove to be a key to successful modelling of GRBs and XRFs that are sometimes associated with such events.

Here, we present the deepest yet search for the progenitor of type Ic SN 2004gt, using Keck laser-guide-star assisted adaptive-optics (LGSAO) observations (§ 2) to pinpoint its location to within 0.06 arc seconds and overcome source confusion in pre-explosion Hubble Space Telescope (*HST*) data, a major limitation in some previous studies. We impose the first far UV, and deepest yet optical and IR, upper limits on the luminosity of the SN progenitor (§ 3). These rule out a luminous ($M_V < -5.5$, $M_B < -6.5$) Wolf-Rayet (W-R) star exploding as SN 2004gt.

2. Observations

On 28.48 January 2005 UT, forty seven days after the first report (Monard 2004) about the type Ic (Ganeshalingam, Swift, Serduke, & Filippenko 2004) supernova SN 2004gt, we undertook high angular resolution observations in the 2.2-μm (K_s) band of the SN and its vicinity using the wide-field channel (0.04 arcsecond/pixel) of the Near Infra-Red Camera 2 (NIRC2) operated behind the newly commissioned Laser Guide Star (LGS) assisted Adaptive Optics (LGSAO; Wizinowich et al. 2004) system mounted on the Keck II 10-m telescope on Mauna Kea, Hawaii. An artificial beacon is created in the sky by shining a strong laser beam, tuned to the resonance line of sodium, up into a sodium-rich layer, usually located at an altitude of ≈ 90 km. Using the beacon, the adverse blurring effects of the lower altitude atmosphere are measured and then corrected by a deformable mirror. The laser beacon is insensitive to tip-tilt corrections but we were able to use the SN itself for this purpose. The data were reduced in the standard manner, with bias-subtraction, flatfielding, fringe calculation and subtraction, image registration, cosmic ray identification, cosmic ray and bad-pixel masking, and final image combination performed using custom software within the Pyraf environment. The resulting images, with full width at half maximum (FWHM) of 0.13 arcseconds (more than 3 LGS pixels, so well-sampled), have exquisite resolution (Figure 1), comparable to the angular resolution of images produced by the *Hubble Space Telescope* (HST).

HST observations of the vicinity of SN 2004gt prior to its explosion were extracted from the HST archive. Available data include Wide Field and Planetary Camera 2 (WFPC2) imaging in the F336W (4500s), F439W (4000s), F555W (4400s) and F814W (2000s) bands ($UBVI$ respectively, hereafter) obtained during January 20, 1996. The location of SN 2004gt falls on the better-sampled (but less sensitive) PC chip, with pixel scale 0.05 arcsecond/pixel. Additionally, we examined a single 720s far-UV image obtained with the

Space Telescope Imaging Spectrograph (STIS) using the far-UV MAMA detector and the F25SRF2 filter, obtained on June 21, 1999. The WFPC2 data were reduced by custom software using elements from the DRIZZLE (Fruchter & Hook 2002) IRAF package (see Sand et al. 2005) and photometered using the HSTPHOT package (Dolphin et al. 2000).

3. Upper limits on the luminosity of the progenitor of SN 2004gt

Our LGSAO observations of SN 2004gt were motivated by three reasons. First, the empirical constraints on progenitors of type Ic supernovae are poor (§ 1). Second, there exists a treasure trove of archival (pre-supernova) HST observations of NGC 4038/4039, covering the entire UV/optical wavelength range (1500 Å to 9000 Å; § 2). Third, the exquisite image quality of the LGSAO images means that we can pinpoint the location of the SN, and hence its progenitor, among the numerous stars and star clusters visible in this part of the host galaxy (see Figure 1).

We register the Keck-LGS K_s-band and archival *HST* I-band images in the following manner. We choose the I-band *HST* image to minimize the effect of any wavelength-dependent centroid shifts for objects used in the registration. We perform coarse alignment using six bright sources, and then make a finer alignment using the eleven sources indicated by circles in panels Figure 2 (a) and (b). The IRAF tasks "geomap" and "geotran" are used throughout, and a general second-order transformation is applied. We then register the remaining *HST* images against the I-band image using the same tasks. We determine the final uncertainty in the SN location on the pre-explosion *HST* images by adding in quadrature the SN centroiding error (Fig. 1), the RMS error in the *HST* I-band to Keck K_s-band registration, and (where relevant) the RMS error in registration between the *HST* I-band image and the target image. We find 1σ total uncertainties of 0.24 to 0.31 Keck (LGS) pixels depending on the band ($\sim$0.01 arcsecond). Figs. 1(b) and 3 show the final 5σ

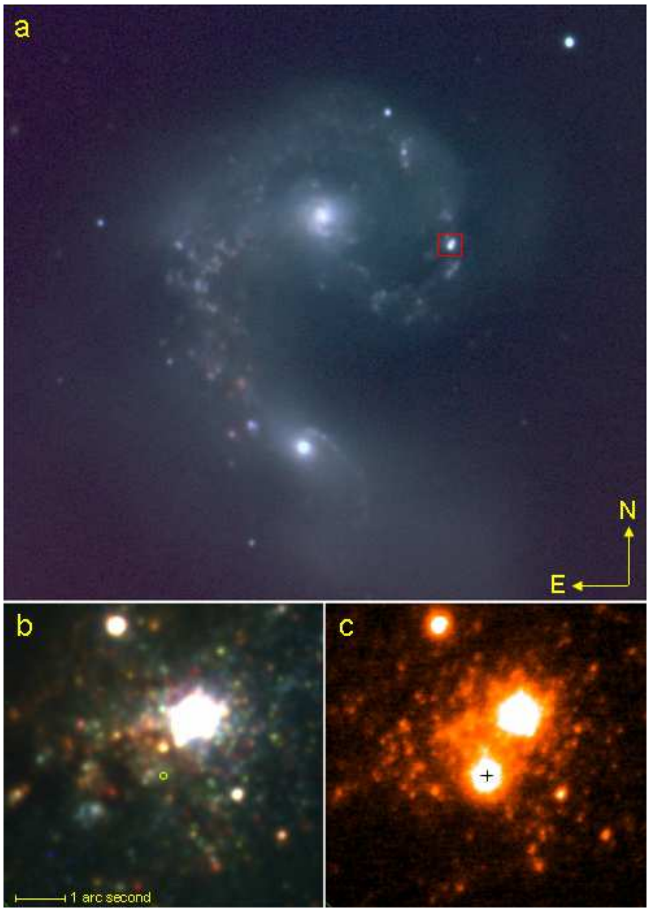

Fig. 1.—

(a) Composite near-infrared (JHK_s) image of SN 2004gt and its host galaxy, the Antennae, taken on 16 January 2005 UT within the context of our ongoing CCCP program at Palomar Observatory (Gal-Yam et al. 2004b). The SN (centered within the red square) is barely resolved from the bright cluster "S" to its northwest (Whitmore et al. 1999). **(b)** The vicinity of SN 2004gt (red square in panel a), prior to its explosion, as seen in the far-UV to I-band by *HST*. The color composite uses far UV (STIS 1450 Å) and U-band (WFPC2 3360 Å) images for blue, B-band (WFPC2 4390 Å) and V-band (WFPC2 5550 Å) images for green, and the I-band (WFPC2 8314 Å) image for red. The yellow circle gives our 5σ uncertainty in the SN position on this image (see Fig. 2). **(c)** SN 2004gt and its immediate vicinity at high-resolution in K_s-band (0.13 arcsecond full-width at half-maximum). The SN location (indicated by the cross) is determined to <0.05 pixel precision (0.002 arcsecond) using the centroid finding algorithm within IRAF.

error circles.

As can be seen from Figure 3(a)-(d) we could not identify any distinct progenitor star at the location of SN 2004gt in any of the available archival HST images. Following Gal-Yam et al. (2004a) we estimate our limiting magnitude for an associated point source (progenitor star) as follows. We derive our photometric zero-points from bright and well-isolated stars using the *HSTPHOT* package (Dolphin 2000). Introducing artificial stars of progressively fainter magnitude (panels e-g, where the B-band image is used for illustration) at locations (indicated by stars) with background levels consistent with the location of SN 2004gt (indicated by the circle), we determine the limiting magnitude for detection of a point-source (f), as contrasted with the brightest non-detection (g). We derive limiting magnitudes of $m_U = 22.7 \pm 0.5$, $m_B = 24.65 \pm 0.15$, $m_V = 25.5 \pm 0.15$ and $m_I = 24.4 \pm 0.3$, where our errors are dominated by the uncertainty in the local zero point. The far-UV STIS data (h) present a special case, as this detector-filter combination has not been extensively calibrated. First, we note that although a single pixel near the SN location appears elevated, it is only a 1.5σ excursion above the brightness of nearby pixels and is derived from a single image. Second, our estimated limiting magnitude of $m_{farUV} = 23.4$ is calculated via photometric coefficients in the image header ($PHOTFLAM = 3.951175 \times 10^{17}$ and $PHOTZPT = -21.1$), and using a 0.5 arcsecond aperture.

Adopting the most recently determined distance to the Antennae galaxies, $d = 13.8 \pm 1.7$ Mpc (Saviane, Hibbard, & Rich 2004) the magnitude limits result in the progenitor star being fainter than 1.25×10^4 solar luminosities in the V band. The corresponding absolute magnitudes are $M_U > -8.0$, $M_B > -6.05$, $M_V > -5.2$ and $M_I > -6.3$. These limits are $\approx 2 - 10$ times tighter than any previously obtained (§ 1).

It is important to quantify the effect of interstellar dust between us and the supernova. In this direction interstellar extinction by Galactic dust is small, $E_{B-V} = 0.012$ magnitude

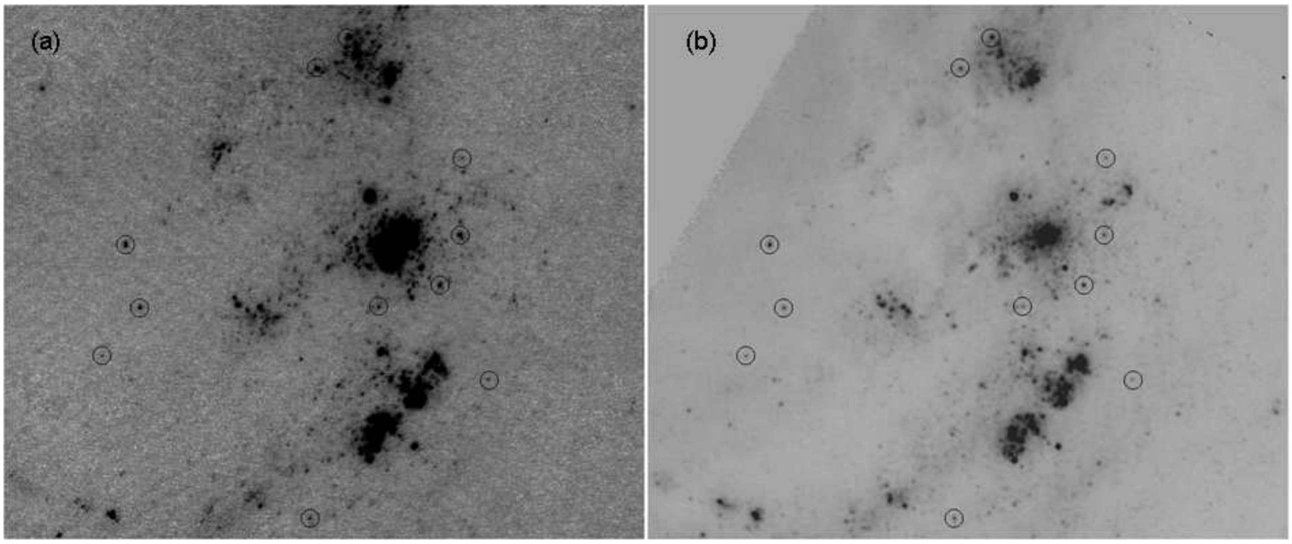

Fig. 2.— Registration of Keck-LGS K_s-band (a) and archival *HST* I-band (b) images. Using 11 stars common to archival HST images and our LGS image (circled) we are able to register SN 2004gt onto pre-explosion images, to within <0.06 arcsecond, at 5-σ confidence level. Figs. 1(b) and 3 show the final 5σ error circles. Each panel is 28×24 arcseconds, North is up and East to the left.

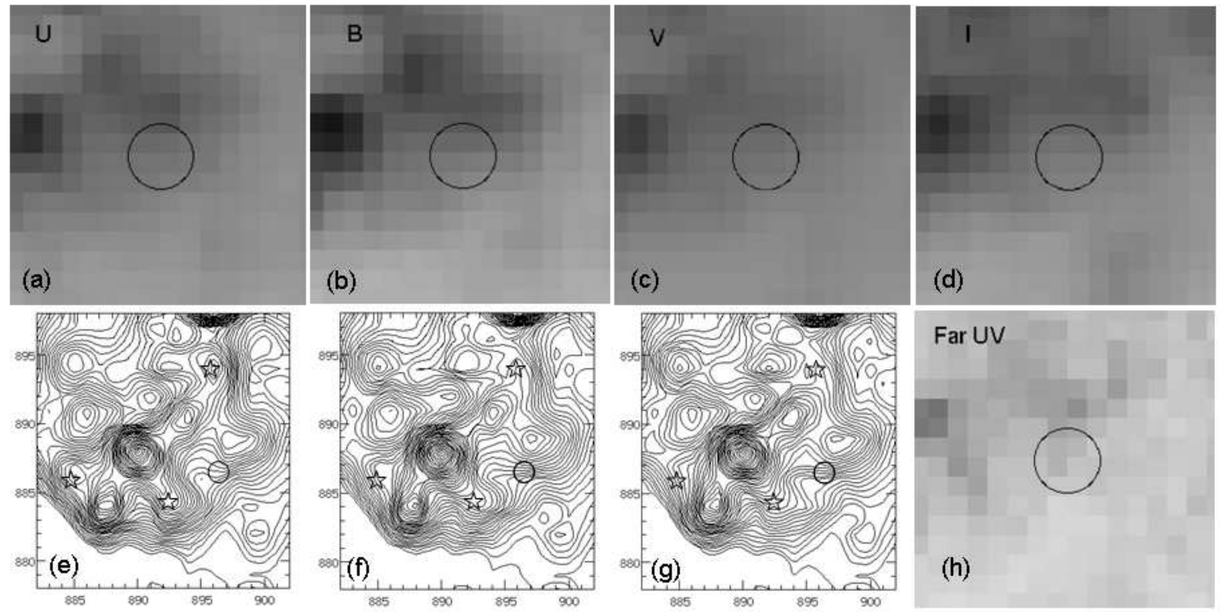

Fig. 3.— Pre-explosion *HST* images of the immediate vicinity of SN 2004gt, in five bands, and illustration of our sensitivity estimation method. Coadded *HST* images in the U (a), B (b), V (c), and I-bands (d) shows no point-like source within the 5σ localization region for the SN. Panels (e)-(g) demonstrate our sensitivity estimation (the B-band data are shown for example). We insert artificial sources with known flux into locations (stars in panels (e)-(g)) with background levels similar to those we measure at the position of SN 2004gt (circle). Panel (e) shows a clear detection while panel (f) a marginal one. We set our limit as the brightest non-detection (g). We find that any putative progenitor had to be fainter than apparent magnitudes, $m_U = 22.7$, $m_B = 24.65$, $m_V = 25.5$, $m_I = 24.4$ and $m_{\lambda=150\mathrm{nm}} = 23.4$. Panel (a)-(d) and (h) are 0.64×0.64 arcseconds across, while panels (e)-(g) are 0.8×0.8 arcseconds. In all cases North is up and East is to the left.

(Burstein & Heiles 1982) to 0.046 magnitude (Schlegel, Finkbeiner, & Davis 1998). Whitmore et al. (1999) report their photometric and spectroscopic analysis is consistent with the lower value of the two which they consider negligible, and which we also adopt (but do not neglect) here. In the same work, the extinction, inferred from HST ultra-violet (UV) spectroscopy, of the star cluster clearly seen in the vicinity of SN 2004gt (Figure 1) is also low, $E_{B-V} = 0.01 \pm 0.04$ (Whitmore et al. 1999). The equivalent width, W, of the Na I D-absorption lines in SN spectra has been argued (Turatto, Benetti, & Cappellaro 2002) to be a tracer of interstellar gas (and thus also of dust). From a spectrum of SN 2004gt obtained using the DBSP spectrograph mounted on the 200" Hale telescope at Palomar Observatory as part of the CCCP program (Gal-Yam et al. 2004a) we measure $W = 0.6\,\text{Å}$, leading to $E_{B-V} = 0.09$ to 0.27 magnitude. In view of the small extinction towards the nearby cluster, we favor the lower value of extinction for the SN itself. Thus, assuming $E_{B-V} = 0.012$ mag and $E_{B-V} = 0.09$ mag for the Galactic and host extinction, respectively, we find the extinction-corrected limits $M_U > -8.6$, $M_B > -6.5$, $M_V > -5.5$ and $M_I > -6.5$.

4. Discussion and conclusions

SNe of type Ib and Ic exhibit no hydrogen in their spectrum. Their progenitors must be massive stars which have lost their hydrogen envelope. This could result from wind-driven mass-loss is very massive stars, $M > 25 - 40 M_\odot$ according to different models (see, e.g., Maeder & Conti 1994 for a review) – such stars are identified locally as Wolf-Rayet (W-R) stars. Alternatively, a lower-mass star in a close binary system may lose its outer envelope through interaction with its companion (see Podsiadlowski et al. 2004 and references therein).

Within the W-R class, the observed range of spectral properties has been further mapped onto an evolutionary path (Maeder & Conti 1994). Of those W-R stars whose spectra are dominated by helium and nitrogen features, consistent with products of hydrogen burning via the Carbon-Nitrogen-Oxygen cycle, the cooler but more luminous ("late") WNL stars are believed to be less evolved than the hotter, but less luminous ("early") WNE stars. Members of the WC and WO subclasses, whose carbon and oxygen-dominated compositions are indicative of helium fusion products, are thought to be more evolved still, displaying material from the deeper stellar layers on their highly stripped surface.

Our observations allow us to conclude that the progenitor of SN 2004gt was fainter than the median star in the compilation (Vacca & Torres-Dodgen 1990) of Galactic WR stars[3]. More importantly, on luminosity grounds, the progenitor is not a WNL star, since, adopting our estimated extinction and distance to the Antennae, we would have detected every WNL star listed by Vacca and Torres-Dodgen[4]. This clue – that the progenitor of SN 2004gt, if a W-R star, must have been a WNE, WC or WO star – directly suggests that type Ic supernova explosions, deficient in both hydrogen and helium, result from evolved progenitors. An immediate corollary would be that progenitors of type Ib SNe (hydrogen poor, but helium-rich) could be among the less-evolved and more luminous WNL stars. This finding is in general accord with our current theoretical understanding of how stars evolve, and constitutes the first direct support of this picture. We note that SN Ib/c models invoking less massive, lower-luminosity progenitors in binary systems, cannot be constrained by our observations.

The observations presented here bode well for making rapid progress in relating the

[3]We correct the narrow-band v magnitudes given by Vacca & Torres-Dodgen (1990) to broad-band (Johnson) V magnitudes (similar to the F555W WFPC2 filter we analyze) by applying individual $V - v$ corrections to each star which we derive using the SIMBAD database.

types of SNe to their progenitors, a subject currently dominated primarily by theory and models. LGS observations on large-aperture telescopes have the necessary sensitivity and precision to routinely localize SNe relative to archival high resolution images of their host galaxies. Currently the *Hubble Space Telescope* provides the best archive of nearby galaxies. However, as LGS methodology becomes more common it is quite conceivable to undertake a dedicated program of imaging the ≈ 1000 nearest galaxies known to contain significant populations of massive stars, in preparation for future SNe. The goal of this effort would be to empirically link the nature of exploding stars and the properties of the resulting explosions, from which we can understand the physical processes that govern one of Nature's most dramatic events, the explosions of dying stars as SNe, gamma-ray bursts and X-ray flashes.

Note added

While this manuscript was being refereed, similar work by Maund, Smartt, & Schweizer (submitted to ApJL) has become public. These authors use late-time *HST* data to localize SN 2004gt, and analyze the same pre-explosion WFPC2 data. The SN localization and progenitor upper limits they derive appear to agree with our results, as do their estimated dust extinction, leading them to arrive at similar conclusions.

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