LUMINOSITY AND MASS LIMITS FOR THE PROGENITOR OF THE TYPE Ic SUPERNOVA 2004gt IN NGC 4038

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Abstract

We report on our attempts to locate the progenitor of the Type Ic supernova SN 2004gt in NGC 4038. We use high-resolution HST ACS images of SN 2004gt and have compared them with deep pre-explosion HST WFPC2 F336W, F439W, F555W, and F814W images. We identify the SN location on the pre-explosion frames with an accuracy of 5 mas. We show that the progenitor is below the detection thresholds of all the pre-explosion images. These detection limits are used to place luminosity and mass limits on the progenitor. The progenitor of SN 2004gt seems to be restricted to a low-luminosity high-temperature star, either a single WC star with an initial mass of \(\geq 40 M_\odot\) or a low-mass star in a binary. The pre-explosion data cannot distinguish between the two scenarios.

Subject headings: galaxies: individual (NGC 4038) — stars: evolution — supernovae: general — supernovae: individual (2004gt)

1. INTRODUCTION

Stellar evolution models predict that all stars with \(M_{\text{ZAMS}} \geq 8 M_\odot\) should end their lives in a core-collapse–induced supernova (CCSN) explosion (e.g., Heger et al. 2003; Eldridge & Tout 2004). The identification of the progenitor of a CCSN just prior to explosion provides a critical test for models of stellar evolution. The task of finding the progenitors is complicated by the unpredictable nature of SNe. The two nearby supernovae SN 1987A (Walborn et al. 1989) and SN 1993J (Aldering et al. 1994) had progenitors identified shortly after discovery. Modern telescope archives have allowed the search for progenitors to be increased to large distances (Maund & Smartt 2005; Van Dyk et al. 2003). In order to confidently identify the correct star as a SN progenitor on images of the highest resolution, precise astrometric techniques are required. Recently, Maund & Smartt (2005) and Smartt et al. (2004) have used high-resolution post-explosion images with the Hubble Space Telescope (HST) and the technique of differential astrometry to accurately identify progenitors on pre-explosion HST images. The brightness and color information from pre-explosion images may then be used to place the progenitor on the Hertzsprung-Russell (H-R) diagram (e.g., SN 2003gd; Smartt et al. 2004). There are no detections yet of progenitors of the hydrogen-deficient Type Ib or Ic SNe, although upper limits to their absolute magnitudes have been determined (see § 4). It is now thought that some Type Ic SNe produce gamma-ray bursts (GRBs; Matheson et al. 2003; Hjorth et al. 2003) and that the progenitors may be rapidly rotating massive Wolf-Rayet (W-R) stars.

This Letter presents the study of HST Wide Field Planetary Camera 2 (WFPC2) images of the site of SN 2004gt in the interacting galaxy NGC 4038, prior to explosion. SN 2004gt was discovered by L. A. G. Monard (Monard et al. 2004) on 2004 December 12.076 with an unfiltered magnitude of 14.6, corresponding to an absolute magnitude of \(\approx 17\) at the distance of NGC 4038 \([m-M]_0 = 31.4;\) Whitmore et al. 1999). The position of SN 2004gt was given as \(\alpha_{2000} = 12^h01^m50.37^s, \delta_{2000} = -18^\circ52'12.77''\) (Ganeshalingam et al. 2004) classified SN 2004gt as Type Ic. The WFPC2 data are the deepest, and widest wavelength coverage, pre-explosion images of any nearby Type Ibc SNe to date, and they provide a unique opportunity to study the progenitor site of a possible GRB-related supernova event. Gal-Yam et al. (2005) use post-explosion ground-based imaging with adaptive optics, and similar pre-explosion HST WFPC2 data, and identify the same location for the progenitor of SN 2004gt and draw similar conclusions about its nature to those presented here.

2. OBSERVATIONS AND DATA ANALYSIS

The pre-explosion HST WFPC2 observations of the site of SN 2004gt were obtained on 1996 January 20 with F336W (4500 s), F439W (4000 s), F555W (4400 s), and F814W (2000 s) filters. The pre-explosion WFPC2 observations (programme GO-5962; PI: B. Whitmore), in each filter, are drizzled combinations of four separate exposures. These four exposures were acquired in pairs, for the rejection of cosmic rays, with an offset of 0.25 between pairs of exposures (Whitmore et al. 1999). The progenitor of SN 2004gt fell on the Planetary Camera (PC) chip for which the pixel size of the drizzled image was 0.025 (the same as the HST Advanced Camera for Surveys [ACS] High Resolution Channel [HRC]). Aperture photometry was performed on the final images using the IRAF implementation of DAOphot and the prescription of Whitmore et al. (1999). Empirical aperture corrections were calculated for each frame, and small charge transfer inefficiency corrections (~0.01 mag) were applied to the photometry using the prescription of Dolphin (2000b). The photometry was converted to the standard Johnson-Cousins system using the transformations of Holtzman et al. (1995) with the updates of Dolphin (2000a).

DAOphot provides four centering algorithms to calculate the locations of stars: centroid, ofilter, Gaussian, and point-spread function (PSF) fitting. The scatter in the measured locations of stars was used to describe the uncertainty due to the undersampled PSF of WFPC2. Post-explosion ACS/HRC images (programme GO-10187; PI: S. Smartt) were acquired on 2005 May 16 with the F435W (1672 s), F555W (1530 s), and F814W (1860 s) filters. These images were analyzed using the PyRaF implementation of DAOphot, using Tiny Tim PSFs (Krist & Hook 2004) for PSF photometry. Empirical aperture corrections to 0.5" were calculated for each frame (with the correction for 0.5" to \(\approx 0.75\) taken from Sirianni et al. 2005), and the photometry was corrected for charge transfer inefficiency according to the...
relationships of Riess & Mack (2004). The ACS photometry was converted to standard Johnson-Cousins magnitudes using the transformations of Sirianni et al. (2005). The photometry was found to agree with results from the DOLPhot package, an update of HSTPhot (Dolphin 2000a) to ±0.1 mag at m ≈ 25. The locations of 16 stars common to both the pre-explosion WFPC2 imaging and the post-explosion ACS imaging were used to calculate the transformation between the two sets of F555W images, using the IRAF task geomap. The positions of stars on the ACS frame were transformed to the coordinates of the drizzled PC F555W image with an accuracy of ±5 mas. The reverse transformation has an uncertainty of ±4.6 mas. SN 2004gt is located 1.3, approximately south, from knot S (Whitmore et al. 1999).

3. OBSERVATIONAL RESULTS

SN 2004gt is readily identifiable on post-explosion ACS images. We measure the apparent brightness and colors of SN 2004gt on 2005 May 16 as $m_V = 18.55 \pm 0.12$, $B-V = 0.87 \pm 0.16$, and $V-I = 1.32 \pm 0.15$. The location of SN 2004gt and its position on the WFPC2 pre-explosion images are shown in Figure 1. The limiting magnitude at the position of SN 2004gt on the pre-explosion frames was determined using the technique of Maund & Smartt (2005). Aperture photometry was done over a 9-point grid centered at the SN position, with offsets of 1 pixel that permitted background variations, over the aperture area, to be taken into account. The detection thresholds determined in this manner were tested by adding a scaled PSF at the SN position on the pre-explosion magnitude. This tested whether or not the DAOPhot photometry would recover a star at the calculated detection threshold. The detection thresholds determined to be $m_{F336W} \approx 23.04$, $m_{F439W} \approx 24.56$, $m_{F555W} \approx 25.86$, and $m_{F814W} \approx 24.43$.

The post-explosion ACS photometry of stars within 2" was used to estimate the reddening toward SN 2004gt using the technique of Maund & Smartt (2005). The photometry of 47 nearby stars was used to estimate the reddening as $E(B-V) = 0.07 \pm 0.01$. This low reddening is consistent with the foreground reddening as quoted by NED, after Schlegel et al. (1998), and the reddening determined by Whitmore et al. (1999) toward knot S. The shape of the continuum of an early spectrum of SN 2004gt (K. Kinugasa 2005, private communication) did not show evidence for significant reddening, being similar in shape to early-time spectra of SN 2002ap [$E(B-V) = 0.09$; Mazzali et al. 2002].

The detection thresholds, calculated above, were converted to absolute magnitudes taking into account the distance and extinction toward NGC 4038. We calculated the extinctions in WFPC2 bands, using the $A_V/E(B-V)$ relations of Van Dyk et al. (1999), to be $A_{F336W} = 0.39$, $A_{F439W} = 0.30$, $A_{F555W} = 0.20$, and $A_{F814W} = 0.13$. This implies the progenitor on the pre-explosion frames had magnitudes $M_{F336W} \approx -8.75$, $M_{F439W} \approx -7.14$, $M_{F555W} \approx -5.74$, and $M_{F814W} \approx -7.10$.

An age for the environment around SN 2004gt was estimated by comparing the positions of nearby stars on a color-magnitude diagram with theoretical isochrones (we use the stellar evolution tracks and isochrones of the Geneva stellar evolution group). The isochrones were shifted for the distance, extinction, and reddening of NGC 4038. Assuming the standard Galactic extinction-reddening relationship of $A_V \approx 3.1E(B-V)$ and $E(V-I) = 1.6E(B-V)$, the value of the reddening calculated above yielded $A_V = 0.22 \pm 0.03$ and $E(V-I) = 0.11 \pm 0.05$. The mean age of the nearby stars was measured to be log (age/yr) = 6.93 ± 0.13, or 8.5 ± 2.5 Myr. This age is consistent with the age of 7 ± 1 Myr estimated by Whitmore et al. (1999) for knot S. The age of the nearby stars corresponds to the lifetime of stars with $M_{ZAMS} \approx 20–40 M_\odot$.

4. DISCUSSION

Maund & Smartt (2005), Smartt et al. (2002), and Van Dyk et al. (2003) have shown how the pre-explosion photometry may, in the event of the nondetection of the progenitor, be used to place mass limits on the progenitor. The pre-explosion detection thresholds were converted to luminosity thresholds for a range of supergiant spectral types, using the colors, temperatures, and bolometric corrections given by Drilling & Landolt (2000). In addition, synthetic photometry was conducted on model W-R spectra (Gräfener et al. 2002; Maund & Smartt 2005), using the STSDAS packages synphot, to calculate the colors and bolometric corrections for these types of stars. These colors and corrections are dependent on two parameters: the effective temperature and the “transformed radius.” Maund & Smartt (2005) discuss how the two-parameter space of model spectra was sampled to completely measure the spread in colors and bolometric corrections. The principal consequence of this two-parameter dependence is that at high temperatures, when...
the progenitors are expected to be W-R stars, the uncertainty in the luminosity increases with temperature compared to the relationship for supergiants. The observed absolute magnitude detection limits were converted to luminosities using equations (6) and (7) of Maund & Smartt (2005). The detection thresholds for the four different filters were plotted on H-R diagrams, shown in Figure 2, and compared with stellar evolution tracks to estimate mass limits.

The F336W pre-explosion observation does not place a stringent constraint on the progenitor, missing both the red supergiant and the blue W-R endpoints of the stellar evolution tracks for low- to intermediate-mass stars and high-mass stars, respectively. The F439W observation excludes yellow and red supergiant progenitors, for $M_{\text{ZAMS}} \approx 20–25 \, M_{\odot}$ as well as the lowest mass stars that end their lives with a W-R phase ($M_{\text{ZAMS}} \approx 25–40 \, M_{\odot}$). The constraint against a W-R progenitor, with an initial mass of 40 $M_{\odot}$, is weak, however, as the luminosity uncertainty is large. The red supergiant progenitors for stars with $M_{\text{ZAMS}} < 25 \, M_{\odot}$ are completely excluded by the F814W observation (including the location of the progenitor of the Type IIP SN 2003gd; Smartt et al. 2004). The F555W observation places much stronger constraints on both sides of the H-R diagram. The red supergiant progenitors for stars with $M_{\text{ZAMS}} < 25 \, M_{\odot}$ are completely excluded (including the location of the progenitor of the Type IIP SN 2003gd; Smartt et al. 2004). A much tighter constraint on the W-R branch excludes an $M_{\text{ZAMS}} \approx 25–40 \, M_{\odot}$ progenitor. All four pre-explosion observations clearly indicate that the SN 2004gt was not the result of the explosion of a supermassive $M_{\text{ZAMS}} \approx 120 \, M_{\odot}$ star. The depth of the observations, despite not being sufficient to detect the progenitor, provides useful limits on the progenitor of SN 2004gt. The use of the smaller distance of 13.8 ± 1.7 Mpc to NGC 4038, determined by Saviane et al. (2004), would result in the threshold limits on the H-R diagrams being lowered by ∼0.28 log $L_{\odot}$. The consequence of this would be to increase the likelihood of the detection of a W-R star progenitor arising from stars with initial masses ∼40 $M_{\odot}$. This shift is, however, smaller than the uncertainties of the thresholds on the blue side of the H-R diagram. The pre-explosion observations do not exclude possible blue lower mass progenitors in binaries, with $M_{\text{ZAMS}} = 20–40 \, M_{\odot}$ as given by the age determined for the surrounding stellar population. The evolution of such a progenitor would have been affected by angular momentum and mass exchange with a companion, which would strip the progenitor’s H envelope leaving a low-luminosity high-temperature He and C-O star as the progenitor (Podsiadlowski et al. 2004). Maund & Smartt (2005) have suggested this as a possible explanation for the lack

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**Fig. 2.**—H-R diagrams showing solar metallicity stellar evolution tracks. Overlaid are the detection thresholds for the pre-explosion HST WFPC2 F336W, F439W, F555W, and F814W images. A progenitor lying in the hatched regions would have been significantly detected.
of detection of a number of progenitors of Type Ibc SNe. This progenitor scenario was also invoked by Nomoto et al. (1994) for the Type Ic SN 1994I. Podsiadlowski et al. (2004) argue that the prompt collapse of a single star would produce a faint SN, whereas SN 2004gt is of normal brightness. The distance to NGC 4038, 19.2 Mpc, is prohibitive to conducting a spectroscopic search for the companion (Maund et al. 2004). In Table 1 we compile all the directly measured upper limits for the magnitudes of the progenitors of Type Ibc SNe, in various passbands. We can determine the upper final mass limit, i.e., the mass prior to explosion, of a W-R star progenitor from the mass-luminosity relationship of the Langer models (Langer 1989). These upper limits are somewhat higher, although not inconsistent with the calculated final mass of the star that produced SN 2002ap (5–7 $M_\odot$), which includes $\sim 2 M_\odot$ allowance for a compact remnant, determined from modeling the spectral evolution of the supernova (Mazzali et al. 2002). Vacca & Torres-Dodgen (1990) give the range of observed absolute magnitudes for Galactic WN stars as $M_V = -3.2$ to 8.0. Assuming a uniform distribution in absolute brightness implies that the pre-explosion observations are sensitive to $\sim 50\%$ of WN stars, mostly WNL stars. The luminosities of WC stars in the LMC (Crowther et al. 2002) are $L/L_\odot < 5.8$, which places them within the lower uncertainty boundary for the detection of W-R stars (see Fig. 2). This shows that these observations cannot constrain the progenitor scenario by themselves. A comparison of these final upper mass limits may, however, be used with SN evolution models and their mass budget to constrain a W-R progenitor scenario. Understanding the progenitors of Type Ic SNe, whether high-mass W-R stars or low-mass stars in binaries, is important for understanding the relationship between SNe and GRBs (Hjorth et al. 2003). The high rate of SN events in the merging galaxies NGC 4038/4039 (Neff & Ulvestad 2000) in conjunction with the large amount of deep imaging of this system available suggests that NGC 4038/4039 is a good candidate for the detection of progenitors of Type Ibc SNe in the future.

The location of SN 2004gt, in the galaxy NGC 4038, in pre-explosion HST WFPC2 images has been identified using differential astrometry with a post-explosion high-resolution HST ACS observation of SN 2004gt. The progenitor location was identified with an accuracy of 5 mas. The progenitor was not detected in any of the deep F336W, F439W, F555W, and F814W pre-explosion imaging. The detection thresholds of the pre-explosion observations suggest that SN 2004gt arose from a single star progenitor with $M_{\text{ZAMS}} \approx 40 M_\odot$ or a $M_{\text{ZAMS}} \approx 20–40 M_\odot$ star in a binary. This is the most restrictive mass limit placed on any Type Ibc SN yet, and this is attributable to the depth of the available pre-explosion imaging.

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TABLE 1

| Supernova | Type | $M_\text{lim}^\text{F606W}$ | $M_\text{lim}^\text{F555W}$ | $M_\text{lim}^\text{F814W}$ | $M_\text{lim}^{\text{HST}}$ |
|-----------|------|--------------------------|--------------------------|--------------------------|--------------------------|
| 2000ds..... | Ic   | ...                      | ...                      | ...                      | ...                      |
| 2000ew..... | Ic   | ...                      | ...                      | ...                      | ...                      |
| 2001B..... | Ic   | ...                      | ...                      | ...                      | ...                      |
| 2002ap..... | Ic   | ...                      | ...                      | ...                      | ...                      |
| 2004gt..... | Ic   | ...                      | ...                      | ...                      | ...                      |

Notes.—Limits are from this Letter, Smartt et al. (2002), and Maund & Smartt (2005), with the corresponding bolometric luminosity limit calculated from Maund & Smartt (2005). The limiting magnitudes for SN 2002ap have been adjusted for the new large distance to M74 as determined by Hendry et al. (2005). The $M_{\text{lim}}$ magnitudes for SN 2000ds are $HST_{\text{lim}}$, and $M_{\text{lim}}$ for SN 2000ew and SN 2001B are $M_{\text{lim}}^{\text{F606W}}$ and $M_{\text{lim}}^{\text{F555W}}$, respectively. For SN 2004gt, the limiting magnitudes $M_{\text{lim}}^{\text{F606W}}$, $M_{\text{lim}}^{\text{F555W}}$, and $M_{\text{lim}}^{\text{F814W}}$ are $HST_{\text{lim}}$, $M_{\text{lim}}^{\text{F606W}}$, and $M_{\text{lim}}^{\text{F814W}}$, respectively.